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Report on economy-wide circularity and the stock-flow nexus for materials-energy-GHG emissions, for EU27+3 countries

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Executive Summary

The deliverable assesses the status and contribution of the circular economy (CE) for climate change mitigation, at the national to European level. Existing analyses and methods are highly aggregated, not stock-flow consistent, and do not link materials to energy and GHG emissions systematically. Key challenges are persistent data gaps regarding material stocks, as well as that official statistics and industry data have varying data ontologies, resolutions and scopes.

To address these issues, we integrate official statistics on raw material extraction, industrial production, waste generation and recycling, by using the dynamic stock-flow model MISO2. This framework enables economy-wide mass-balancing of material cycles and ensures stock–flow consistency. In the extended MISO2+ model, we delineate the associated energy use during extraction and processing of stock-building materials as well as subsequent GHG emissions (direct scope 1+2). The resulting consistent dataset enables novel analyses of the nexus between materials, waste, energy and GHG emissions, and generates macro-level headline indicators on the narrowing, slowing and closing material of material cycles.

We find that economy-wide material use in the EU27 increased from 2000 to 2007, after which it narrowed by around 10% up to 2022. Over the same period, material cycles slowed and closed slightly: material retention times lengthened from 14 to almost 20 years, and the circular material use rate rose from 7% to 12%. Looking at the narrowing, slowing, and closing of material cycles together, we here observe that slowing material cycles does not necessarily lead to much reduced overall material use. To achieve this, also material stocks need to saturate, which grew by 33% since the 2000s to 154 Gigatons across all EU states, requiring substantially more virgin raw materials (in 2022 making of 44% of PM) than were supplied through closed material cycles (11% of PM). Energy use and energy-related GHG emissions linked to stock-building materials declined by 37% and 53% respectively since 1990 — yet they continue to represent about one-third of the EU's total energy use and emissions. In addition, the EU remains strongly dependent on imports of materials such as iron and steel, aluminium, and plastics, underlining the need for international cooperation.

We conclude that a more sustainable circular economy also mitigating GHG emissions requires stabilizing material stocks and prolonging their lifetimes, which would narrow and slow material cycles. Substantially upscaled waste collection and recycling systems are required to close material cycles across more materials and avoid widespread downcycling. International coordination with key trading partners supplying raw materials is also required. Next steps include semi-harmonizing stock-flow data across ongoing modelling efforts in CircEUlar, and then develop counter-factual and narrative-driven scenarios on CE potentials for accelerating climate change mitigation efforts in the European Union. Because the findings presented herein are so far unpublished and are currently being prepared for publication in open-access peer-reviewed scientific journals; they are therefore confidential.



Keyword

economy-wide material and energy flows analysis, circularity indicators, socio-economic material stocks, materials-energy-GHG nexus

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Abbreviations

CircEUlar	Developing circular pathways for a EU low-carbon transition
DE	Domestic Extraction
EJ	Exajoule
EU	European Union
ew-MEFA	Economy-wide Material and Energy Flow Accounting
GHG	Greenhouse gas
IAM(s)	Integrated Assessment Model(s)
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IO	Input-Output
MF	Raw Material Footprint
MISO2	Dynamic inflow-driven global material stock-flow model MISO2 (Material Inputs, Stocks, and Outputs)
MISO2+	MISO2 model extended with raw material extraction, energy use, GHG emissions and circularity indicators
PM	Processed Material
PMP	Primary Material Production
SMP	Secondary Material Production
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WP	Work Package
MISO2	Dynamic inflow-driven global material stock-flow model MISO2 (Material Inputs, Stocks, and Outputs)

1. Introduction

To accelerate reductions of GHG emissions and improve the sustainability of European resource use, the circular economy (CE) has become the major policy strategy to improve upon the environmental and economic performance of the European Union member states (European Commission 2025). The prominence of the CE concept stems from its forward-looking focus on solutions to global environmental challenges (Leipold 2021), its reliance on the widely established metaphor of 'natural cycles' (Skene 2018), and its openness to multiple interpretations — from material cycles to sustainable business profits (Luo et al. 2021). These qualities attract diverse actors and interests under a broad, inclusive umbrella (Blomsma and Brennan 2017; Geng, Sarkis, and Bleischwitz 2019). Depending on the interpretation of the concept (Geissdoerfer et al. 2017; Leipold et al. 2023), some advocate the CE as obvious win-win-win for sustainable development (MacArthur Foundation 2025) 2019, while others call for careful assessments of the CE's potentials, including possible trade-offs and limitations (Corvellec, Stowell, and Johansson 2021; Giampietro and Funtowicz 2020; Leipold et al. 2023). Practically, CE discussions connect existing concepts into a systems-oriented narrative which bridges policy silos and aims to inspire business and non-profit activities (Blomsma and Brennan 2017).

While the CE concept is sometimes simply interpreted as 'more recycling', most academic and public interpretations see the CE as addressing the entire life cycle of materials, products and provisioning systems (Džajić Uršič, Fric, and Rončević 2024; Kirchherr 2023; Korhonen, Honkasalo, and Seppälä 2018). When the CE is interpreted as systems approach, it aims to transform how materials are extracted, processed and used through measures that narrow, slow and close material cycles (Blomsma and Brennan 2017; Džajić Uršič et al. 2024; Kirchherr 2023; MacArthur Foundation 2025). Such a systems-based interpretation of the CE begins with measures to reduce material demand and improve the resource efficiency of products and service provisioning systems (narrow), extend product lifetimes and reduce waste (slow), and increase recycling (close). The expectation is that narrower, slower and more closed material cycles help avoid raw material extraction, reduce energy use and mitigate GHG emissions (Morseletto 2020). Disentangling the specific contributions of these aspects of the CE concept and how they interact and might synergize with other strategies to deliver GHG emission mitigation is therefore an important research frontier (Wiedenhofer, Wieland, Leipold, Aoki-Suzuki, Watari, et al. 2025).

However, methods to quantify the mitigation of GHG emissions through CE measures have not been fully developed yet, and the official monitoring of the relationships between material cycles, CE measures and GHG emissions are not well established. The body of CE research focussing on the micro- and meso-level GHG emission mitigation potentials due to improvements to specific products, technologies and business models has grown rapidly (Hossain et al. 2024; Schöggl, Stumpf, and Baumgartner 2020). However, this micro- and meso-level research usually suffers from ambiguous CE definitions, varying study scopes, as well as a multitude of incompatible methods and data sources (Cantzler et al. 2020; Gallego-Schmid et al. 2020; Hertwich et al. 2019; Mastrucci et al. 2023; Meshulam et al. 2023; Pauliuk 2018). These ambiguities inhibit cumulative insights into the CE's contribution to GHG emissions mitigation at the national to European level, and do not provide continuous monitoring into national-level progress vis a vis policy targets.

For this purpose, macro-level CE monitoring frameworks are required, which cover the entire national to European economy consistently with the System of National Accounts, as well as resource use, waste- and GHG emission accounts (Mayer et al. 2019; Wiedenhofer, Wieland, Leipold, Aoki-Suzuki, Edelenbosch, et al. 2025). National monitoring of economy-wide material cycles and derived CE indicators such as the 'circular material use rate' are used in Japan, China and the European Union (Aoki-Suzuki et al. 2023; Bleischwitz et al. 2022; Mayer et al. 2019). However, the monitoring systems for energy use and GHG emissions are being done completely separately, which means that monitoring systems for materials, energy and GHGs are not systematically integrated This severely limits the understanding of the interrelations between material cycles, waste flows, energy use, GHG emissions and CE measures for national policy and monitoring (Aoki-Suzuki et al. 2023).

In summary, while policy makers around the world expect substantial contributions from the CE for climate change mitigation, these contributions are not yet properly measured nor ensured. Only a small number of countries have quantified circularity targets, which are often not linked to proposed actions nor GHG emission reductions in a science-based manner (Barrie et al. 2024). Translating those policy intentions into official long-term mandates for data gathering and monitoring is crucial to ensure that progress and setbacks can be identified. Evaluating CE policy outcomes is therefore going to be an important future research frontier, to which this deliverable contributes by developing the necessary methods, data and proposals for new indicators.

Herein, we present progress towards comprehensive assessments of economy-wide circularity and the nexus of materials, energy, and GHG emissions for the EU27+3 countries. Innovatively, we integrate multiple official statistics not properly linked so far and use dynamic stock-flow modelling

to achieve a stock-flow consistent assessment. We provide a range of novel empirical insights not yet published, as well as a first set of macro-level headline indicators aiming to monitor progress towards narrower, slower and more closed material cycles. Below, we first clarify how the micro-level CE strategies interact with macro-level resource efficiency and climate change mitigation, drawing on work supported by the project CircEUlar (Leipold et al. 2023; Wiedenhofer, Wieland, Leipold, Aoki-Suzuki, Edelenbosch, et al. 2025) (section 2). We summarize the current state of macro-level CE assessments (section 3), and then outline the necessary improvements and challenges for the next version of macro-level CE monitoring originally developed by some of the authors (Haas et al. 2020; Mayer et al. 2019) (section 4). Subsequently, we document how this novel economy-wide mass-balanced stock-flow consistent CE monitoring framework is developed to assess economy-wide circularity and the nexus between materials-energy-GHGs (section 5). We then quantify economy-wide material stocks and flows, related circularity indicators for narrower, slower and more closed material cycles, as well as the associated energy flows and GHG emissions, for the EU27+3 from 1990 to 2022 (section 6). This is done along basic value chains from extraction, processing and manufacturing to various end-uses in production and consumption as well as end-of-life, waste management, and recycling practices. We finalize with a discussion of results, as well as next steps in the project CircEUlar (section 7).

2. From micro-level CE measures to macro-level resource efficiency and GHG emission mitigation

Herein we conceptualize the CE as a systems concept building on the widely accepted '*reduce, reuse, recycle* (3R)' waste avoidance hierarchy as well as eco-design principles (Prieto-Sandoval, Jaca, and Ormazabal 2018). These 3Rs are nowadays differentiated into 10Rs: *refuse, rethink, reduce, re-use, repair, refurbish, re-manufacture, re-purpose, recycle, recover* (Morseletto 2020; Potting et al. 2017). The CE builds on a rich intellectual history (Blomsma and Brennan 2017) from bio-mimicry (Morseletto 2020; Prieto-Sandoval et al. 2018) to extended producer responsibility (Maitre-Ekern 2021), resource- and material efficiency (Hertwich et al. 2019; Jonathan M. Cullen et al. 2022) as well as sufficiency (Bocken, Niessen, and Short 2022; Velenturf and Purnell 2021). The 10R measures address the micro-level of products and the meso-level of business models and specific production-consumption systems (Geissdoerfer et al. 2017; Morseletto 2020; Potting et al. 2017).

Implementing the 10R measures should lead to narrower, slower and more closed material cycles at the macro-level of the entire economy (Morseletto 2020), which herein we aim to quantify. Narrower cycles are to be achieved by reducing material demand and smarter product use and manufacture (*refuse, rethink, reduce*). Slower material cycles are to be achieved by extending the lifespan of products and their parts (*re-use, repair, refurbish, re-manufacture, re-purpose*). More closed material cycles are to be achieved via the useful application of end-of-life and waste materials (*recycle, recovery*). The CE discussion also distinguishes socio-technical and socio-ecological material cycles, roughly corresponding to non-renewable (metals, non-metallic minerals, fossil energy carriers) and renewable resources (biomass) (Geissdoerfer et al. 2017; Kirchherr 2023; Morseletto 2020).

While narrower, slower and more closed material cycles aim at avoiding waste and reducing virgin raw material demand, they can also play an important role in reducing energy use and GHG emissions from energy supply, industrial processes as well as agriculture, forestry and other land uses (AFOLU) (Morseletto 2020; Wiedenhofer, Wieland, Leipold, Aoki-Suzuki, Edelenbosch, et al. 2025). Importantly, the environmental benefits of CE strategies can only be evaluated at the macro-level as isolated miso and meso measures might lead to worse environmental outcomes through rebound effects, burden shifting and unintended consequences (Pauliuk 2018). The analyses presented below aims to address these issues through quantifying the macro-level status and dynamics of material and energy use, stocks, waste and GHG emissions, substantially advancing the so far available economy-wide CE monitoring framework (Mayer et al. 2019).

3. Status and challenges for macro-level CE monitoring

3.1. Economy-wide material and energy flow accounting

Existing macro-level CE monitoring frameworks all build upon economy-wide material and energy flow accounting (ew-MEFA), which has been established to provide systematic information on domestic resource extraction, physical trade, material stocks and outputs to the environment, applying system boundaries from the System of National Accounts (UNEP 2023). Ew-MEFA aims to provide systematic information on domestic resource extraction, physical trade, material stocks and outputs to the environment (UNEP 2023). Ew-MEFA is designed to be part of the System of Environmental-Economic Accounting (SEEA) and is therefore aligned with the system boundaries applied across socio-economic and environmental indicators, most prominently for GDP (UNEP 2023) (Eurostat 2001; Fischer-Kowalski et al. 2011; Krausmann et al. 2017; OECD 2008) To achieve comparability of ew-MFA studies across spatio-temporal scales, system boundaries and derived indicators have been unambiguously defined and were internationally harmonized (Fischer-Kowalski et al. 2011; Schandl et al. 2024). Nowadays, indicators derived from ew-MFA on annual resource extraction, trade and consumption are widely used for policy and monitoring, based on official statistical reporting of national and international organizations. This widespread use builds on a phase of methodological harmonization in the 2000s (Eurostat 2001; Fischer-Kowalski et al. 2011; OECD 2008) which consolidated work since the first multi-national studies were led by the World Resources Institute in the 1990s (Adriaanse and World Resources Institute 1997; Matthews et al. 2000).

Ew-MEFA is designed to systematically and consistently account for timeseries of material and energy flows crossing the analytical boundary between society and nature (Figure 1) (Fischer-Kowalski and Weisz 1999; Haberl et al. 2004; Pauliuk and Hertwich 2015). Currently available ew-MEFA databases report domestic extraction of primary materials, biophysical imports and exports, as well as derived indicators (Figure 1, mass-balanced flows marked with an asterisk). The myriad of raw materials extracted from nature are currently classified into 45-60 material categories at the most detailed level. These categories are usually presented in summary along four major categories: biomass, metal ores, fossil energy carriers, and non-metallic minerals. Data for ew-MFA is synthesized and harmonized from various statistical reporting systems each operating with their own aims, scopes and system definitions, e.g. agricultural, mining and energy statistics, trade statistics, waste and emission statistics. Those statistics are provided by national statistical offices and international organizations such as the International Energy Agency, Food and Agricultural

Organization of the United Nations, or UN-Comtrade (European Commission. Statistical Office of the European Union. 2018; OECD 2008; UNEP 2023). Material and energy flows are accounted for by applying the mass-balance principle to ensure a thermodynamically correct representation of socio-economic systems. Most empirical research of the socio-economic metabolism utilizing ew-MFA simplifies the socio-economic system into a "black box", focusing on raw material flows into, and waste and emissions out of the system, neglecting processes within (Krausmann et al. 2017).

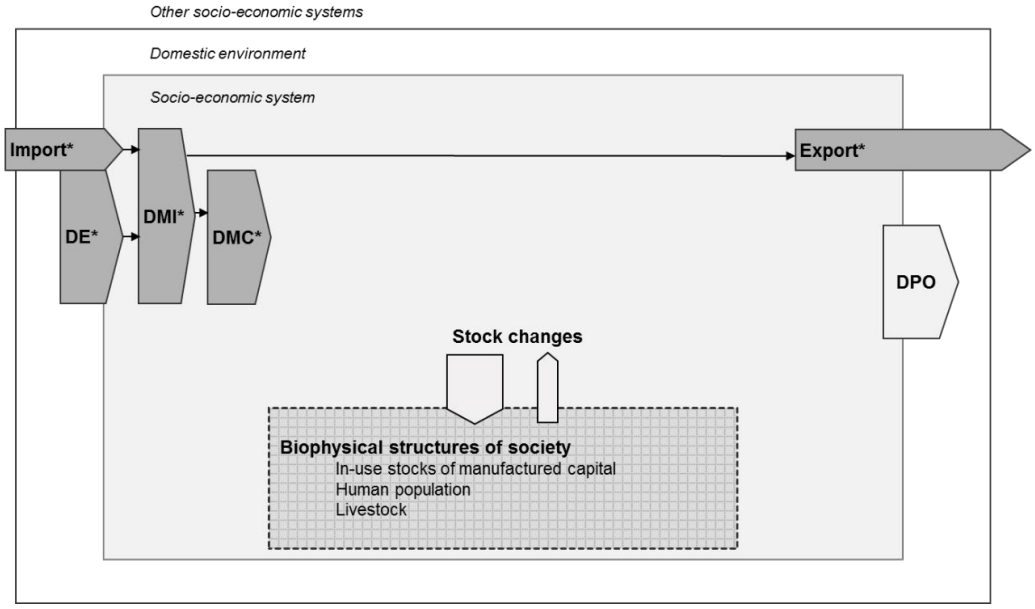


Figure 1: The framework of economy-wide material flow accounting (ew-MFA), based on (Eurostat 2001; Fischer-Kowalski et al. 2011; OECD 2008). Conceptually, a mass balanced quantification of material flows for the entire socio-economic system is to be achieved by balancing 'inputs' such as domestic extraction (DE) and physical imports, to all 'outputs', covering exports and all domestic processed outputs (DPO) of waste and emissions. Derived headline indicators are the Domestic Material Inputs (DMI) and Domestic Material Consumption (DMC). Empirical progress is usually limited to those mentioned flows indicated with an asterisk, while processing steps, industries, and material stocks, as well as the Domestic Processed Outputs are not systematically quantified yet.

In parallel, detailed quantifications of material cycles, energy use and GHG emissions within the socio-economic system have been developed for a wide range of specific substances or materials, often focused on metals (Deng, Zhang, and Fu 2023; Esther Müller et al. 2014; Graedel 2019; Watari, Nansai, and Nakajima 2020).

Several of these works also investigate the CE of different sectors such as buildings, transport and appliances with a high level of detail but do not span the whole economy (Mastrucci et al. 2024; Pauliuk et al. 2021, 2024). For these studies, substantial efforts to develop high-quality datasets on substance and material flows were conducted. However, variable system boundaries and study-specific system definitions inhibit systematic integration of substance/materials/sector-specific

insights into comprehensive economy-wide databases. Systems-oriented economy-wide approaches therefore require further improvements on system definitions, data quality, transparency and harmonization. Efforts are also ongoing which utilize physical (Altimiras-Martin 2014; Wieland et al. 2021) and monetary (Lenzen et al. 2021; Malik et al. 2018) input-output tables to open this black box, linking resource use with production and consumption along (monetary) inter-sectoral relationships. However, so far input-output based approaches suffer from an incomplete treatment of material stocks and their dynamics, and a fully mass-balanced treatment of waste and recycling resulting from economy-wide resource use has only been achieved for specific cases and materials (Majeau-Bettez et al. 2016; Nakamura and Kondo 2009; Pauliuk et al. 2014; Pauliuk, Wood, and Hertwich 2015; Tisserant et al. 2017).

3.2. Circular economy monitoring framework

Based on advances of the ew-MEFA framework, some of the authors of this report also provided the first ever economy-wide assessments of how circular the global and European economy actually are (Haas et al. 2015). The CE monitoring framework originally developed by Haas et al. has been slightly improved by several research teams, for example for the past 115 years of global un-circularity (Haas et al. 2020), as well as insights into the status of the circular economy in the EU27 (Mayer et al. 2019), Austria (Jacobi et al. 2018) South Africa (Haas et al. 2023), China (Wang et al. 2020) and Australia (Miatto et al. 2024). These efforts also fed into the development of the scientific basis for the current EU27 CE monitoring framework, by consistently integrating and mass-balancing information on material extraction and trade, with waste and energy as well as GHG statistics (European Commission 2018; Jacobi et al. 2018; Mayer et al. 2019). The widely popular Circular Economy Gap Reports then use this framework and combine it with a multi-regional input-output model to link with consumption-based material footprints (Circularity Gap Report 2024). However, these first efforts only provided relatively aggregate insights into the status of the circular economy, and did not address material stock dynamics as well as the interlinkages between materials-energy-GHGs from a stock-flow consistent perspective.

3.3. Challenges for an economy-wide assessment of the circular economy

In ew-MEFA studies, flows related to material stock changes, such as gross & net additions to stock per year, as well as waste and GHG emissions (Domestic Processed Outputs to nature per year) are conceptually included in the framework (Figure 1, light grey boxes). However, empirically they have

been rarely addressed, due to a lack of data and mismatching data ontologies (Fischer-Kowalski et al. 2011; Miatto et al. 2025; Schandl et al. 2024; UNEP 2023). Stock-related flows were often approximated via mass-balancing inputs and outputs of the socio-economic system, suggesting full system closure, but actually shifting any inconsistencies and uncertainties into the estimates of stock-related flows. Consequently, methods and indicators for waste and emissions, as well as overall domestic processed outputs are less elaborated and not standardized (Fischer-Kowalski et al. 2011; Kovanda 2017; OECD 2008; UNEP 2023). The key sources and challenges for a fully mass-balanced, stock-flow consistent and materials-energy-waste-GHG explicit monitoring of the circular economy at the national to EU27 macro-level are therefore the following (Figure 2):

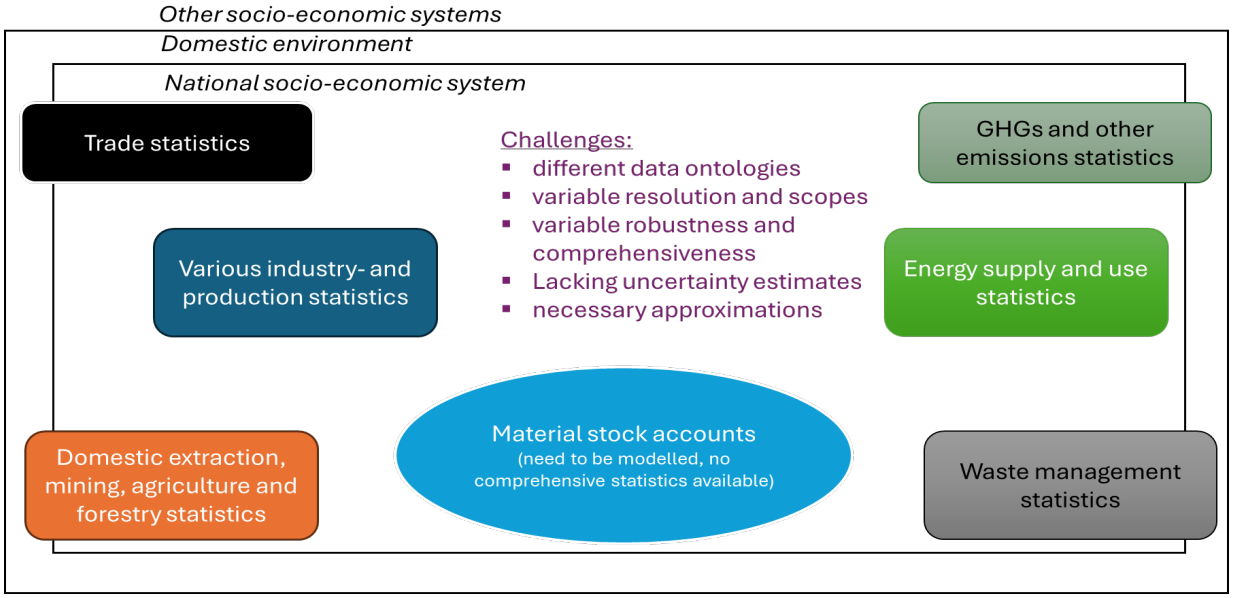


Figure 2: Challenges for an economy-wide assessment of the circular economy and the nexus between materials-energy-GHGs. Source: own compilation.

First, consistently integrating economy-wide material cycles with robust material stock estimates remains a challenge (Streeck et al. 2025). Raw material extraction and land use, which constitute the beginning of material cycles, is reported according to the boundaries established in the SEEA and focuses on types of raw materials, e.g., biomass, non-metallic minerals, ores and metals, and fossil energy carriers, lacking inherent sector resolution (Krausmann et al. 2017). This data is increasingly used and requires researchers to make advances in compiling data on material cycles and waste by-products occurring at each production step, for example via input-output tables or detailed material flow analysis (Plank et al. 2022a; Streeck, Pauliuk, et al. 2023). However, used data sources such as industry production statistics, for instance those for cement or steel, focus on specific stages of the

value chain and material cycle and they are often eclectically and selectively used, without fully mass-balancing to raw material extraction nor waste and recycling (Kullmann et al. 2021; Wiedenhofer, Schug, et al. 2024; Wiedenhofer, Streeck, Wieland, Grammer, Baumgart, Plank, et al. 2024). Also, waste statistics, if available (Tisserant et al. 2017; UNEP and ISWA 2024) , cover only what is officially collected and managed in institutionalized waste management systems, leaving large unknowns (UNEP and ISWA 2024). These challenges substantially hinder the ability to depict how different circular economy measures affect material extraction, land use, material cycles and energy use.

Second, energy statistics report the supply and use of energy carriers for sectors, production processes and final demand, and distinguish between primary, final, and useful energy stages. This information is highly relevant to understand the potentials and limits linked with fuel switching, electrification and energy efficiency (Cullen and Allwood 2010; Sakai et al. 2019), as well as to link energy use with material cycles. However, energy statistics and material cycles data are not linked nor jointly reported, hindering their systematic analysis (Kullmann et al. 2021).

Third, emissions accounting as based on the United Nations Framework Convention on Climate Change (UNFCC) defines the following sectors: energy supply, industry, agriculture and forestry and other land use (AFOLU), transport, and buildings (IPCC 2022; Lamb et al. 2021). This “end-of-pipe” perspective on the ‘sources’ of emissions lacks a differentiation of supply and (final) demand and treats industry as end-user. However, sectors and industries respond to the demand from other sectors, including from final demand. Yet, in current accounting and modelling – with differences depending on statistical practices in each country - industries extracting materials are allocated across energy supply, industry, construction and AFOLU sectors. This substantially limits the possibilities for a consistent analysis of how material cycles, energy use and GHG emissions interlink.

Most existing efforts at reconciling these conflicting data sources either use environmentally-extended input-output analysis (EE-IOA), or economy-wide MEFA (Haberl et al. 2019; Lenzen et al. 2021). EE-IOA uses monetary representations of supply and use across sectors and final demands to allocate biophysical quantities in proportion to monetary relationships, achieving high sectoral resolution. So far however, EE-IOA struggles with explicitly representing material stock dynamics and with tracing actual physical intermediates and final products (Jiang et al. 2023; Stadler et al. 2018). MEFA strictly applies mass-balance and stock-flow consistency to quantify material cycles, incl. waste and processing losses as well as material stocks, however only achieving low to intermediate resolution (Wiedenhofer et al. 2019; Wiedenhofer, Schug, et al. 2024). While so-called

waste input-output analysis (Nakamura and Kondo 2009) combines both approaches, data scarcity inhibits its economy-wide application.

4. Advancing macro-level CE monitoring

4.1. Requirements for consistent macro-level CE monitoring

Assessing progress towards a more circular economy and delineating the CE's contributions to climate change mitigation requires a robust, systematic and consistent economy-wide evidence base. Much of the available evidence is dispersed across studies with varying scopes and system boundaries, therefore providing only limited systems-oriented macro-level insights (Cantzler et al. 2020:202; Deng et al. 2023; Gallego-Schmid et al. 2020; Pauliuk et al. 2024; Watari et al. 2020; Wiedenhofer, Wieland, Leipold, Aoki-Suzuki, Edelenbosch, et al. 2025). Consequently, methodological improvements regarding robustness, transparency, representation of socio-economic material cycles and spatio-temporal coverage are high on the agenda of the scientific community (Hertwich et al. 2018; Pauliuk et al. 2016; Pauliuk and Heeren 2020; Streeck et al. 2025).

Herein, we aim to advance the ew-MEFA based macro-level CE monitoring framework (Haas et al. 2015, 2015, 2023; Jacobi et al. 2018; Mayer et al. 2019; Miatto et al. 2024; Wang et al. 2020). We apply the following principles and aims to disentangle supply and demand as well as circular economy potentials across material cycles, energy use, material stocks, waste and GHG emissions. The advanced ew-MEFA based macro-level CE monitoring frameworks need to:

a) comply with thermodynamics and mass-balance for physical stocks and flows,
b) utilize harmonized definitions and conventions of ew-MEFA and advance them further,
c) introduce sectors and industries through which materials cycle,
d) quantify material product stocks of manufactured capital and their dynamics,
e) quantify flows of secondary (re- or downcycled) materials,
f) integrate waste statistics to fully quantify domestic processed outputs to nature,
g) link energy use and GHG emissions to material cycles.

Currently available macro-level, economy-wide CE (ew-CE) studies address some of these principles (Haas et al. 2020, 2023; Miatto et al. 2024) but do not explicitly address materials-energy-GHG interlinkages, nor do they provide granular insights into the material cycles and energy uses across the socio-economic system. The following section briefly summarizes the three main ew-CE approaches to date.

4.2. Current approaches for macro-level CE assessments

The first seminal macro-level CE assessment was pioneered by (Haas et al. 2015), implemented as a purely flow-based approach. Detailed estimates of global and EU27 Domestic Material Consumption were allocated to either throughputs within the same year (e.g. energy use, dissipative uses, mining and production waste), or stock-building materials, which are assumed to remain in-use for years to decades. The end-of-life materials from stocks are then approximated via a simple leaching-type lifetime function. Modelled end-of-life materials, recycling rates and some data from waste statistics are then used to quantify the amount of secondary materials used, which subsequently enable calculating the indicator 'circular material use rate' (Haas et al. 2015).

The second approach is also purely flow-based but uses multiple data sources to mass-balance its quantification, e.g. by using a rough matching of reported waste statistics as well as GHG statistics to Domestic Material Consumption (Haas et al. 2023; Jacobi et al. 2018; Mayer et al. 2019; Wang et al. 2020). This second generation of macro-level CE studies substantially improved the robustness of results by matching it much more closely with official statistics (as well as showing where there are problems with official waste statistics). However, several assumptions and rough estimations are still required, which were further simplified by EUROSTAT when implementing their version of this CE monitoring framework (European Commission 2018). While this approach achieves full mass-balance, most inconsistencies and data errors end-up in the under-determined approximations of the gross- and net additions to stocks, as well as end-of-life outflows from stocks. The widely popular Circular Economy Gap Report (Circularity Gap Report 2024) as well as a recent study on Australia and its status towards a circular economy (Miatto et al. 2024) builds upon a combination of approaches 1+2, which are then combined with MRIO-based material footprint estimates.

The third approach utilizes a dynamic stock-flow model to quantify end-of-life and waste materials in a stock-flow consistent manner, which requires exogenous information on recycling and downcycling rates for all materials to derive the 'circular material use rate' (Haas et al. 2020). Here, uncertainties and data errors end up as part of the end-of-life waste and recycling estimations, because stock turnover rates (lifetimes) as well as recycling rates were parametrized based on scarce and uncertain empirical data (Wiedenhofer et al. 2019). While this third approach implements stock-flow consistency, it does not explicitly address materials-energy-GHG interlinkages, nor does it provide more granular insights into the material cycles and energy uses across the socio-economic system.

The work presented below builds on top of above approaches following the economy-wide system definition of the SEEA[1] framework and substantially advances the dynamic quantification of material cycles and their interdependence with energy, waste and GHG emissions. These improvements are essential for delineating and capturing how the circular economy affects material, waste, energy use and GHG emissions stocks and flows.

[1] … The SEEA aims to provide integrated economic, social and environmental information (UN, EU, FAO, IMF, OECD, WB, 2014), including economy-wide material flow accounting for raw material extraction, energy statistics for sectoral energy use, as well as UNFCC emissions reporting (Krausmann et al. 2017; UNEP 2023).

5. Method developments and data sources

Below, we first summarize the configuration, system definition and data update of MISO2 to assess dynamics of stock-building material flows (section 5.1-5.2). We updated the model input data used to parametrize the model to version 1.1, which entailed multiple data triangulation efforts, yielding quantitative time series of exogenous model input data from 1990 to 2022, extending upon the previously available data ranging from 1820 to 2016 (Annex section 9). Next, we discuss the extension with non-stock-building material flows to assess economy-wide circularity (section 5.3-5.4), and with energy use and GHG flows (section 5.5), as well as raw material extraction (section 5.6), both related to stock-building material flows — which together we denote as "MISO2+". Finally, we describe the procedure for comparing data on waste management obtained from MISO2+ and Eurostat (section 5.7).

5.1. The MISO2 model on stock-building material flows: system definition, methods, data and update

The MISO2 model quantifies economy-wide material cycles and stock dynamics across multiple *stock-building* materials and end-uses at the national level, which is documented in detail in (Wiedenhofer, Streeck, Wieland, Grammer, Baumgart, Plank, et al. 2024). In summary, MISO2 represents material supply chain processes from raw material extraction, trade, processing, stock-building, use phase of material stocks, as well as waste collection, recycling and downcycling. End-use product groups accumulated as material stocks are differentiated using a refined application of the end-use transfer waste input-output method originally developed in (Streeck, Pauliuk, et al. 2023; Streeck, Wieland, et al. 2023). To understand major sources of uncertainty, one-at-a-time sensitivity and uncertainty testing is conducted, including Monte-Carlo Simulations for the end-use shares modelling (Džubur, Buchner, and Laner 2017), based on a systematic uncertainty assessment of the model input data developed previously (Plank et al. 2022a, 2022b). MISO2 builds upon the ODYM framework (Pauliuk and Heeren 2020) and features of the MISO1 model (Wiedenhofer et al. 2019). MISO2 is implemented in a Python based software framework, utilizing the design principles in Table 1.

Table 1 : Design principles used for the MISO2 model, from (Wiedenhofer, Streeck, Wieland, Grammer, Baumgart, Plank, et al. 2024).

Basic Principles	• Economy-wide dynamic material systems analysis, using inflow-driven stock-flow modelling, mass-balanced for each process, material cycle, and the entire system
Modelling Approach	• Inflow-driven, top-down dynamic stock-flow modelling tracing economy-wide material cycles and stock cohorts by end-use. The retrospective application draws on empirical and extrapolated data, while the prospective capabilities require exogenous assumptions on the development of all model input parameters.
Dissipation	• Recoverable and unrecoverable waste flows are modelled for each process and then traced to waste collection and subsequent recycling, downcycling and final waste.
Spatial Dimensions	• National economy-wide system boundaries are utilized due to data limitations, not spatially explicit.
Uncertainty	• Systematic assessment of model data input uncertainty, covering data reliability, completeness, temporal, geographical and other correlations, as well as the quality of required expert judgements • One-at-a-time uncertainty testing model parameters affect stock estimates • Validation of results against available literature and via mass-balances.

The MISO2 model quantifies stocks and stock-building flows in time-steps of one year and for the political-administrative national system boundaries established in economy-wide material flow accounting, in line with the System of National Accounts (UNEP 2023; Wiedenhofer et al. 2019). Material supply chains from extraction to end-use and waste management are differentiated into 14 processes (denoted as *P1-P14* in Figure 3). Nine processes transform materials into products, as well as recoverable and unrecoverable waste. The remaining five processes are defined as international markets connecting trade flows (Figure 3). Because production data in some cases does not match net trade data, which potentially leads to negative estimates of apparent consumption, each market has its own balancing item *B*, which ensures that mass balances between imports, exports and inputs from the previous processes cannot become negative. Splitting material flows into end-uses is introduced in *P9*. In the use phase *P10*, material stocks are traced as annual cohorts of materials by end-uses. End-uses include the different use categories such as buildings or machinery and comprise final consumption of materials in products by households, the public sector, and industrial investments. P11 to P14 handle waste collection, waste trade, recycling and downcycling, as well as final waste management. Recycling is defined as the secondary material entering the same material cycle again; primary downcycling is only modelled for non-metallic construction minerals, following a design-induced and functional downcycling (Helbig et al. 2022), where bricks, concrete, bitumen, and asphalt end up in mixed construction and demolition waste streams and are crushed and sometimes washed to replace primary 'virgin' sand and gravel aggregates. For model-technical reasons only, a buffer process *P-buffer (P20)* is used to transfer materials recycled within a given year, into the next time interval where they are fed into the market for raw products *P4*.

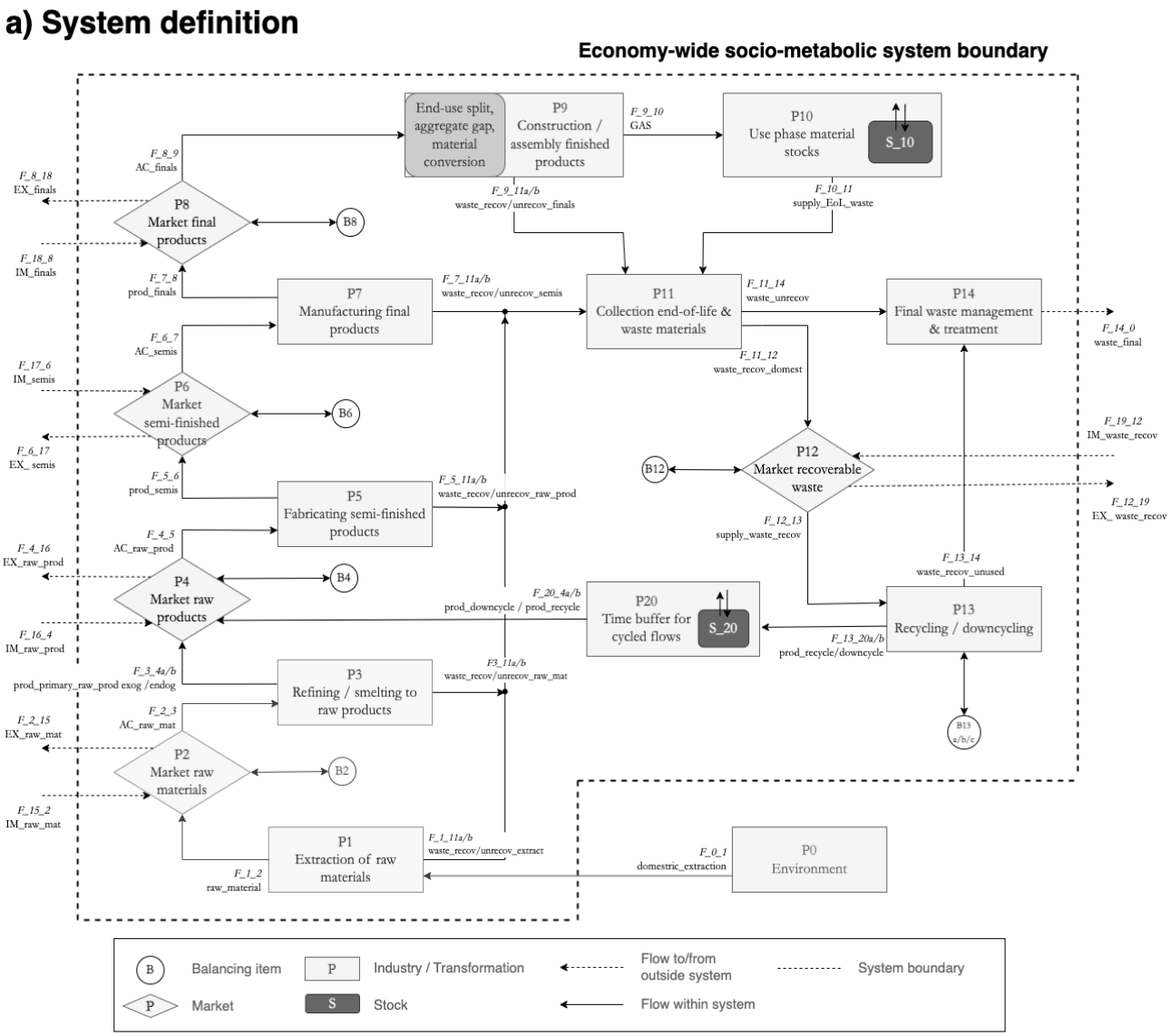


Figure 3: System definition for the MISO2 model (a), and scope of the MAT_STOCKS database version 1.0 (b), from Wiedenhofer et al. (2024). We refer to the supplementary information for definitions of each flow F, process P, balancing items B, as well as documentation on exogenous and endogenous model data inputs and data outputs and the software architecture in which MISO2 is implemented.

The MISO2 dataset v1.0 covers 20 stock-building materials, linked to the extraction of 12 raw materials as reported in ew-MFA and 13 end-use product groups (Table 2). So far excluded are agricultural biomass (e.g., cotton, straw), some fossil-fuel derived materials (e.g., glues, paint, lubricants, etc.), as well as minor metals and rare earth elements due to scarce data at resolution. However, compared to the bulk materials covered, these excluded materials can be expected to represent only a very minor share by mass.

Table 2: Resolution of materials and end-use product groups covered in the MISO2 input datasets version 1.0 as well as the resulting MAT_STOCKS database version 1.0 (Wiedenhofer, Streeck, Wieland, Grammer, Baumgart, and Plank 2024).

Resolution of stock-building material cycles in MISO2	
Biomass materials:	solid wood products and construction timber (1), paper and paperboard (2)
Metals and ores:	iron and steel (3), copper (4), aluminum (5), lead (6), zinc (7), chromium (8), manganese (9), nickel (10), tin (11)
Fossil-fuels derived materials:	plastics (12), bituminous building materials (13), asphalt (14),
Non-metallic minerals:	concrete (15), bricks (16), primary sand and gravel aggregates (17), downcycled construction minerals as secondary aggregates (18), flat glass (19) and container glass (20)
Resolution of end-use product groups in MISO2	
Buildings:	Residential, non-residential
Infrastructure:	Roads, civil engineering
Stationary machinery:	Machinery, computer, electrical equipment
Transport machinery:	Motor vehicles, other transport
Short-lived products:	Furniture, printed matter, food packaging, products not elsewhere specified

Exogenous model data inputs are all physical imports and exports, as well as national materials production in *P3*. End-use shares in *P9* are exogenously modelled. Log-normal lifetime distributions per end-use and material in the use phase *P10* are sourced from the literature, as are recycling and downcycling rates and flows for *P13* and *P14*, as well as the parameters for recoverable and unrecoverable waste rates in *P1, P3, P5, P7, P9, P11, P13* and *P14*. The uncertainty of all exogenous model input data is systematically assessed, following procedures developed previously. While MISO2 dataset v1.0 only ran to the year 2016, we updated the dataset within the CircEUlar project, now reaching to the year 2022. Data updates were implemented for data on material production, trade and recycling (see Annex section 9 for detailed documentation of the update).

Endogenous model data outputs are mass-balanced material cycles for all flows from *P4* to *P14* and annual cohorts of material stocks by material and end-use in *P10*. For more details on MISO2, we refer to (Wiedenhofer, Streeck, Wieland, Grammer, Baumgart, and Plank 2024).

5.2. The MISO2+ extension: economy-wide circularity, energy use, GHG flows and raw material extraction

The MISO2+ extensions expand the system definition of MISO2 regarding energy use and GHG emissions associated with stock-building material flows, as well as adding non-stock-building material flows to assess economy-wide circularity. Thus, in comparison to the original MISO2, several elements are added to the system which are important with regards to the work presented herein: First, dissipative material use and energy supply are added and close the gap to overall, economy-wide material use by adding non-stock-building material flows from economy-wide MEFA. Second, more resolution on the output side is provided, laying the ground for future circularity metrics.

The system definition of MISO2+ (Figure 4) restructures the system definition of MISO2 shown above (Figure 3) into the following groups: the supply of materials and energy (P10x, beige), a hybrid use-phase (P20x), in which biophysical flows are dissipated (P201, white) and short-lived goods and stocks are used (P202; P203 red), to satisfy final demand (P30x, red). The reddish colouring of stocks shall highlight that those are a hybrid of both supply and demand. The waste collection, trade and management processes (P40x, purple) are further disaggregated into a module containing multiple CE measures aimed at slowing and closing cycles. End-of-life products and materials start at a collection point (P401), including international trade of secondary materials and products (P402), with several CE options to extend product (P403-407) or material lifespans (P408-409), energy recovery (P410) or final waste treatment (P411). All transforming processes in the system require energy supply (P109, blue flows) and emit GHG (red flows).

In the text below, we describe the design of these modules and refer to the terminology of processes P, stocks S and flows F of the original MISO2 model which are depicted in Figure 3.

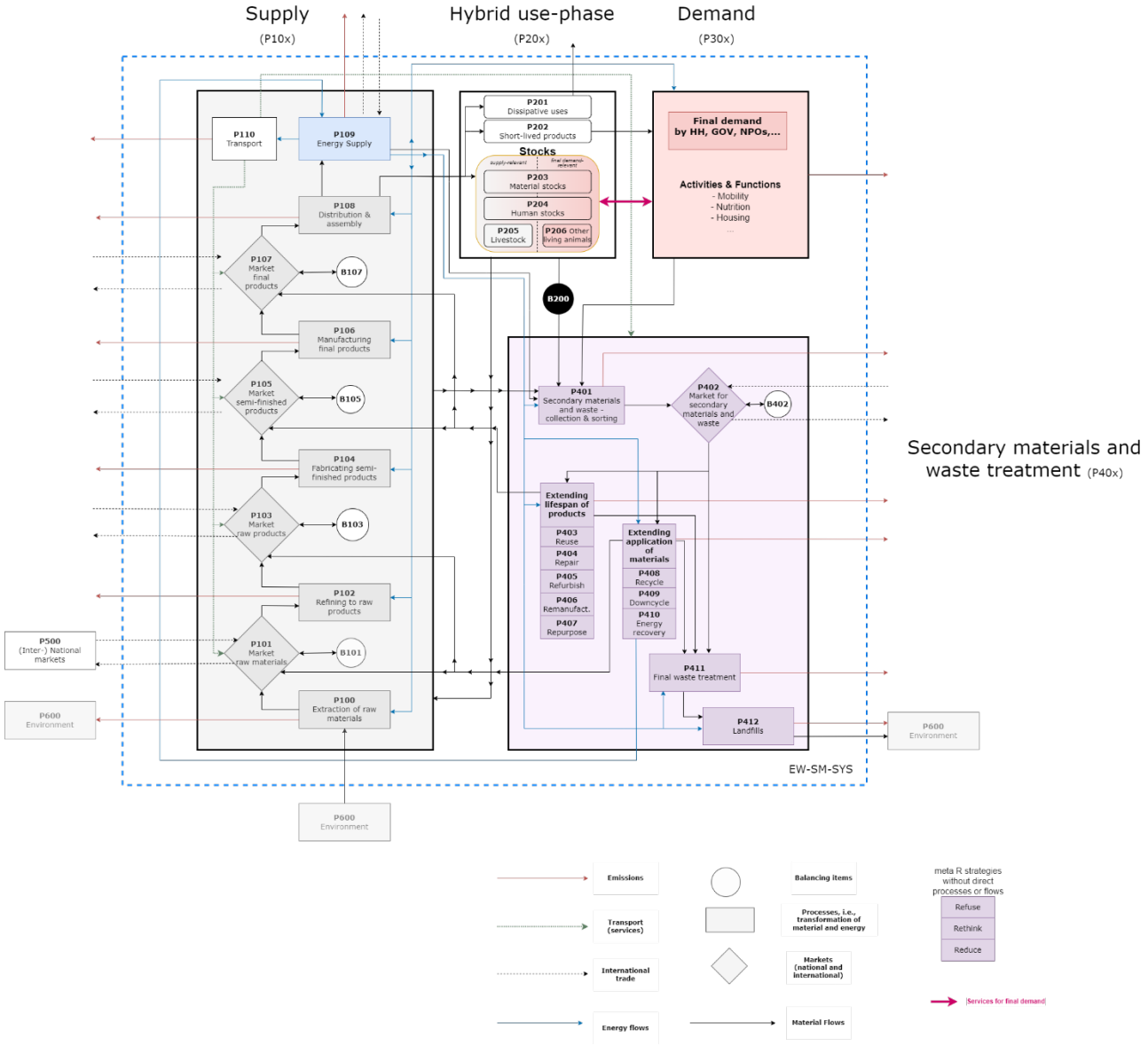


Figure 4: MISO2+ system definition extending the MISO2 definition with energy and GHG flows, as well as economy-wide circularity assessment. The definition was developed based on merging aspects of previous work from MISO2, economy-wide material and energy flow accounting, and economy-wide circularity assessment (Haas et al. 2020; Mayer et al. 2019; Potting et al. 2017; Wiedenhofer, Streeck, Wieland, Grammer, Baumgart, and Plank 2024)

5.3. Integrating stock-building material flows with ew-MEFA accounts to assess economy-wide circularity

A consistent dataset to assess economy-wide material and energy flows as well as their circularity for the EU27+3 countries is created through integration of MISO2 v1.1 data on stock-building material flows and stocks with ew-MEFA accounts of overall domestic extraction (DE), physical imports (IM) and physical exports (EX) from the International Resource Panel (IRP) (Schandl et al. 2024).

The MISO2 v1.1 database contains data on stock-building material flows. From this source, we extract data on secondary (recycling and downcycling) material flows as well as gross additions to stocks (GAS) and end-of-life outflows (EOL) from discarded stocks which are detailed for specific end-uses (e.g., construction or machinery). We aggregate the 20 material types in MISO2 to the four main material groups of ew-MEFA (biomass, metals, non-metallic minerals and fossil fuel-derived materials).

Flows of stock-building materials not covered in MISO2 (e.g. ornamental stones) and all non-stock-building material flows (i.e., energy use, biomass for food and feed, throughput through dissipative use, material processed wastes) are derived by triangulating MISO2 data with IRP's ew-MEFA accounts through mass balancing in which the IRP data is used as constraint, which means that the flows of biomass, fossil fuels, non-metallic minerals and metals are consistent with IRP's accounts for DE, IM and EX. We used IRP instead of Eurostat ew-MFA data because we found the latter not suitable for the envisioned analysis (EU27+3 from 1990 to 2022) due to its limited regional (no data for United Kingdom) and temporal (data for many countries starts in 2000) scope. Only for analysis of the EU27 as aggregate region, we had to rely on trade data from Eurostat (available 2000-2022), as these data without trade between member states is not available from IRP.

In the analysis, we classify 'energy use' as technical energy use of materials as well as food for humans and feed for livestock. Flows of biomass and fossil fuels for energy use are estimated by subtracting the respective sum of gross additions to stocks + throughputs + exports from 'processed materials' (PM = DE + IM + Recycling flows). Metals and metallic minerals are not for energy use.

'Throughput flows' stand for all other material flows that are not added to material stocks, meaning their lifetime is shorter than 1 year, which includes such flows like packaging materials, fertilizers or wastes from material processing that are more or less rapidly discarded to the natural environment

(domestic processed outputs; DPO). Material processing wastes from metals and non-metallic minerals are also classified as throughput and estimated by subtracting the sum of gross additions to stocks + exports from PM.

After estimating economy-wide energy use and throughputs, we calculate the missing inputs and outputs of waste treatment and subsequently DPO via mass balances.

5.4. Operationalization of indicators to assess economy-wide circularity

To assess economy-wide circularity, we draw on the balanced accounts of economy-wide material and energy flows and stocks with MISO2 v1.1 as described in the prior sub-section. From these economy-wide balanced stocks and flows, we calculate indicators for narrowing, slowing and closing material cycles drawing on established literature and own conceptualization (Table 3).

For the *CE dimension narrow*, we assess the temporal development of the indicator processed materials (PM/year) - the sum of domestic extraction of raw materials, overall imports and recycling flows. PM/year represents the overall material use in a socio-economic system such as a country (including for exports). A shrinking of PM/year thus means that material cycles are narrowing in a relative sense (which does not necessarily mean that they are at a sustainable level of resource use).

For the *CE dimension slow,* we assess the material retention time in a socio-economic system, i.e. the relation of PM/year to the accumulated material stocks in the system. This ratio serves as a proxy for the residence time of materials in the socio-economic system. Developments towards a ratio favouring material stocks over PM/year indicates that material cycles are slowing, i.e. that materials remain longer in use within the socio-economic system. The indicator has already been formulated in Tanikawa et al. (2022) where it is named ‘stock retention time’. We renamed it for the purpose here, as its reference to PM does not reflect the residence time of stocks but of materials overall.

For the *CE dimension close*, we use the previously established circular material use rate (CMU), which represents the share of recycling input flows in overall DMC/year, as utilized by Eurostat (Eurostat - Material flows 2025), although here we do not consider waste trade. In the literature also conceptualizations using PM/year, equalling the DMC/year plus yearly exports exist (e.g., (Jacobi et al. 2018). An increasing CMU means that the system is moving towards more closed material cycles. A CMU of 100% would illustrate perfectly closed cycles, which however is theoretically impossible according to the laws of thermodynamics (Cullen 2017). For our own estimates, recycling flows

Table 3: Definition of CE indicators used in this report along the narrow-slow-close dimensions.

CE dimension	Indicator	Definition	Unit of measurement	Source
Narrow	Processed Materials (PM)	Domestic extraction + imports + recycling flows	Tons/year	Proxy of own choice
Slow	Material retention time (MRT)	Material stocks / PM	Years	(Zhang et al. 2022)
Close	Circular Material Use Rate (CMU)	Recycling flows / (PM-exports)	Percent	(European Commission 2018; Haas et al. 2015; Mayer et al. 2019)

include the MISO2 flows recycling (F_20_4a) and downcycling of bricks, asphalt and concrete to aggregates used in building and road foundations (F_20_4b). Eurostat includes flows reported as *Recycling* in their waste accounts.

It is important to note that these three CE indicators should be assessed together, as material cycles which are relatively slow and closed might still consume huge amounts of resources and cause related environmental problems. For instance, the material retention time (slow) shall be assessed together with the development of PM (narrow) because material cycles might be slowing if simply the material stocks grow faster than PM – although this does not prevent that the overall use of materials (PM) grows to infinity and causes environmental havoc. We calculated the above indicators for the EU27 total (not EU27+3 because Eurostat data for comparison was only available for 27 countries) and selected country cases which exhibit interesting trajectories along the indicators.

5.5. Quantifying energy use and GHG emissions in MISO2+

For MISO2+, we quantified the energy use and greenhouse gas (GHG) emissions associated with the use of fossil-fuels in manufacture of *stock-building* material flows (i.e., excluding process emissions and effects of land-use changes). We calculated industrial energy use and GHG emissions for stock-building materials in the EU27, plus Norway, Switzerland, and the United Kingdom, for the period 1990–2022. To this end, we combined a bottom-up approach, based on process-specific energy and GHG intensities, with a top-down approach, based on statistics on sectoral energy use (including heat and electricity) and GHG emissions. The ecoinvent database (version 3.9.1; Cut-Off Classification) (Wernet et al. 2016) and reported direct energy and GHG flows served as the primary data source

for the bottom-up approach, while the IEA Extended World Energy Balances (IEA - A 2025) and IEA Greenhouse gases from Energy (IEA - B 2025)(detailed estimates, IEA Sectoral Approach) provided the data basis for the top-down approach. Bottom-up flows of non-CO_2 GHG emissions were converted to CO_2-equivalents using the AR5 GWP100 via conversion factors provided by the IEA (IEA - B 2025).

First, we established concordances between the MISO2 datasets and the resolutions of both top-down and bottom-up approaches to estimate energy use and GHG emissions. Specifically, we defined the energy requirements of each MISO2 process for each material and end-use (e.g., clinker and cement production for cement in P3; see Annex Table 9) and mapped MISO2 processes, materials, and end-uses to IEA energy flows reported for final consumption (e.g., cement production in P3 to IEA energy flow for non-metallic minerals; see Annex Table 10). Second, we collected bottom-up energy intensity factors ("direct energy input") from the ecoinvent database and additional publications (see next paragraph for details), converted all values to megajoules per kilogram, and multiplied them by the respective MISO2 flows to obtain bottom-up energy use estimates per country, year, and material/end-use (eq. 2). Third, we scaled these bottom-up results to align with the energy use reported by the IEA, thereby ensuring consistency with IEA-reported historical accounts but retaining MISO2's material and end-use resolution. Finally, bottom-up GHG emissions were derived by converting the estimated energy use, using process energy carrier shares (e.g. gas and electricity) reported in ecoinvent, multiplied by IEA emission factors (IEA 2024)(including electricity and heat). As with energy use, bottom-up GHG emissions were adjusted to match the IEA's reported sectoral totals. In other words, we proportionally allocated the IEA's reported energy use and GHG emission accounts for each sector to MISO2 processes, materials, and end-uses, according to their relative contribution to the sector's total, based on multiplication with energy intensities.

The calculation procedure to obtain energy use (EU) and GHG emissions (GE) for each region/country (r), material or end-use (mg), and year (t) was as follows (eq. 1):

$$EU_{r,mg,t} = \frac{bEU_{r,mg,t} * tEU_{r,i,t}}{\sum_{mg=1}^{MG_i} bEU_{r,mg,t}} \qquad eq.\ 1$$

with (eq. 2)

$$bEU_{r,mg,t} = EI_{mg} * F_{r,mg,t} \qquad \textit{eq. 2}$$

and *bEU = bottom-up energy use, , tEU = top-down energy use for sector i (reported from IEA;* see Annex Table 10*), EI = energy intensity, F = MISO2 material flow, i =IEA final consumption sector* MG_i *= set of all materials/end-uses in IEA sector category i*

and (eq. 3)

$$GE_{r,mg,t} = \frac{bGE_{r,mg,t} * \ tGE_{r,i,t}}{\sum_{mg=1}^{MG_i} bGE_{r,mg,t}} \qquad \textit{eq. 3}$$

with (eq. 4)

$$bGE_{r,mg,t} = \sum_{s=1}^{S_{mg}} EU_{r,mg,t,s} * EF_s \qquad \textit{eq. 4}$$

and *s = energy source,* S_{mg} *= set of all energy sources used for this material/end-use, EF = emission factor*

We deviated from this standard procedure in the following specific cases. For motor vehicle production and plastic recycling, where coinvent did not provide sufficient factors, we complemented the data with intensity values from scientific literature. (Babel et al. 2020; Meys et al. 2020; Sato and Nakata 2020; Yan 2009).

Furthermore, as shown by (Harvey 2024) the energy reported by the IEA for the iron and steel industry only covers part of the sector's total energy use. We therefore integrated the energy used for blast furnaces and coke ovens, as reported in the "Transformation processes" section of the IEA database. The IEA sector "Chemical and petrochemical" covers ISIC Rev. 4 Divisions 20 and 21 (excluding petrochemical feedstocks), which include the manufacture of chemicals and chemical products (including primary plastics) as well as pharmaceuticals, medicinal chemicals, and botanical products. Many of these products are not covered in the MISO2 input data, as their contribution to

stock-building is negligible. To exclude energy use for non-relevant products (e.g., fertilizers) while retaining plastics, we estimated the share of plastics in this sector as 69% (Gabrielli et al. 2023).
Similarly, MISO2 only accounts for non-biomass textiles. We therefore subtracted the share of biomass textiles (e.g., cotton) from the IEA "Textiles" sector, assuming the same distribution as global fibre production (32%, resulting from 57% polyester, 5% nylon, and 6% cellulosic fibres). (Textile Exchange 2024)
We classified the IEA industry sectors (including blast furnaces and coke ovens, as described above), along with agriculture, forestry, and fishing, as *industrial*. Energy use and GHG emissions from the IEA categories *transport*, *residential*, *commercial and public services*, and *non-specified (other)* were classified as *operational*.

Due to scope limitations, we restricted the present analysis to energy-related emissions; however, the extension to include chemical process emissions (e.g., clinker production) is already available and will be incorporated in future analyses to provide a more comprehensive assessment. Additionally, for biogenic materials, net effects of land-use changes should be incorporated for holistic assessment.

5.6. Constructing global extraction-production accounts for stock-building material flows in MISO2+

The extraction-production accounts extend the *stock-building* material flows from the global stock-flow model (MISO2) with the related, country-level raw material extraction - including associated extraction-related energy use and CO_2 emissions (excluding non-CO2 emissions here). The creation of the accounts triangulates data sources and identifies substantial data conflicts through the difficulties in the balancing (see below), and by resolving those can show the interlinkage of primary material production in the EU27+3 with upstream raw material extraction on a global scale via international trade.

We compiled physical input-output tables (PIOTs) for twelve stock-building materials on a global scale, covering 177 countries and (depending on the material) three to four processes/flows per material, in a time series from 2007 to 2022. We conducted a footprint analysis of primary material production to uncover import and trade dependencies of production activities in the EU27+3. All PIOT results shown in the result section 6.5 refer to 2022.

PIOTs depict material flows (in metric tons) exchanged between industries, processes, producers, users, and the natural environment in a mass-balanced manner. This provides a detailed, consistent, top-down perspective on the physical economy (Nakamura 2011; Weisz and Duchin 2006; Wieland et al. 2021). PIOTs are particularly useful for tracing material and energy flows alongside waste generation and emissions across multiple activities and regions. A fundamental principle of physical IO is that process inputs equal process outputs, reflecting the laws of conservation of mass and energy. Process balances ensure that top-down accounts are internally consistent, which is essential for reliable analysis and modelling. In physical terms, this means that all materials and energy entering a system (boundary inputs from nature) must be transformed into products, by-products or waste (boundary outputs).

The construction of PIOTs requires balancing algorithms (such as RAS) to reconcile the mismatch between different raw data sources and to find a compromise solution (Geschke et al. 2019). RAS is a widely used matrix balancing technique that adjusts the elements of an initial estimate matrix to satisfy given constraints, such as row, column totals (i.e. process balances) or other data sources (e.g., MISO production data). It operates iteratively by scaling matrix elements alternately with updating factors (see Annex Figure 32 depicting the evolution of updating factors of MISO production data constraints) until the IO table conforms to the specified constraints. This method is computationally efficient and has been applied extensively in input–output analysis (Miller and Blair 2009).

The compilation of the physical IO-based extraction-production accounts uses raw data from MISO2 (primary and secondary production), the domestic extraction accounts and information on regional ore grades from IRP's ew-MEFA accounts (Schandl et al. 2024), as well as international trade data from BACI (Sampaolo 2025). Informed assumptions are made on processing yields and other transfer coefficients that are sourced from the relevant MFA literature e.g., for aluminum see (Bertram, Martchek, and Rombach 2009). Table 4 and Figure 5 depict the system structure of the 12 material processing chains that are modelled in the physical IO tables.

Table 4: Overview over the material processing chains for which detailed extraction accounts were constructed and physical IO analysis was performed. Raw materials mark the starting point and primary material production end point of the processing chain. Note that other inputs (e.g. alloying metals) are also considered in the IO analysis but not explicitly shown here. The physical IO tables are fully mass-balanced.

Material processing chain (labels used in result section)	**Raw material extraction (DE)** (inputs from nature; IRP)	**Primary material production (Y)** (semi-finished output; MISO)
Aggregates	Sand and gravel	Aggregates for concrete, asphalt & base layers
Aluminum	Bauxite	Aluminum
Bitumen_plastic	Oil and gas	Bitumen and plastic
Chromium	Chromium ore	Chromium (metallurgical and other)
Copper	Copper ore	Copper
Iron_steel	Iron ore	Crude steel
Lead	Lead ore	Lead
Manganese	Manganese ore	Manganese (metallurgical and other)
Nickel	Nickel ore	Nickel (metallurgical and other)
Tin	Tin ore	Tin
Wood_paper	Timber	Wood and paper
Zinc	Zinc ore	Zinc

IRP and MISO extraction and production data are used as constraints in the RAS balancing run whereas trade data and other sources are only used for setting up the initial estimate. 500 iterations were performed with RAS to make sure that the results converge to a consistent picture that respects selected data on raw material extraction and primary production as well as the mass balance principle. Note that other inputs (e.g., alloying metals) are also represented in the physical IO tables but not used as constraining values and not explicitly listed in Annex Figure 31. Figure 32 depicts the updating factors for the MISO production data constraints for 2022 (shown in matrix Y in Figure 5). When updating factors converge to 1, the values realized in the PIOT are equal to the associated constraint, meaning MISO data is realized in the PIOTs. Additional plots on the RAS updating factors for process balances and market balances are contained in the Annex section 9.4)

The two largest stock-building raw material flows (in terms of mass) absent from the present physical IO account are clays (approximately 5 Gt/yr in 2022) and limestones (6.7 Gt/yr), which are primarily used for the production of bricks and concrete. The compilation of IO tables for the production activities of glass and bricks was not undertaken. The modelling of limestone flows turned out to be difficult due to its wide range of possible applications, including such uses as a flux in steelmaking. The IO-based analysis of non-metallic mineral flows presented in the report exclusively focuses on aggregates (derived from sand and gravel), which are destined for use in the production of concrete, asphalt, and the base layers of buildings and roads. Nevertheless, the presented physical IO

assessment covers the largest part of all global stock-building material extractions and associated extraction-related CO2 emissions (excl. non-CO2 GHGs) and energy use in 2022.

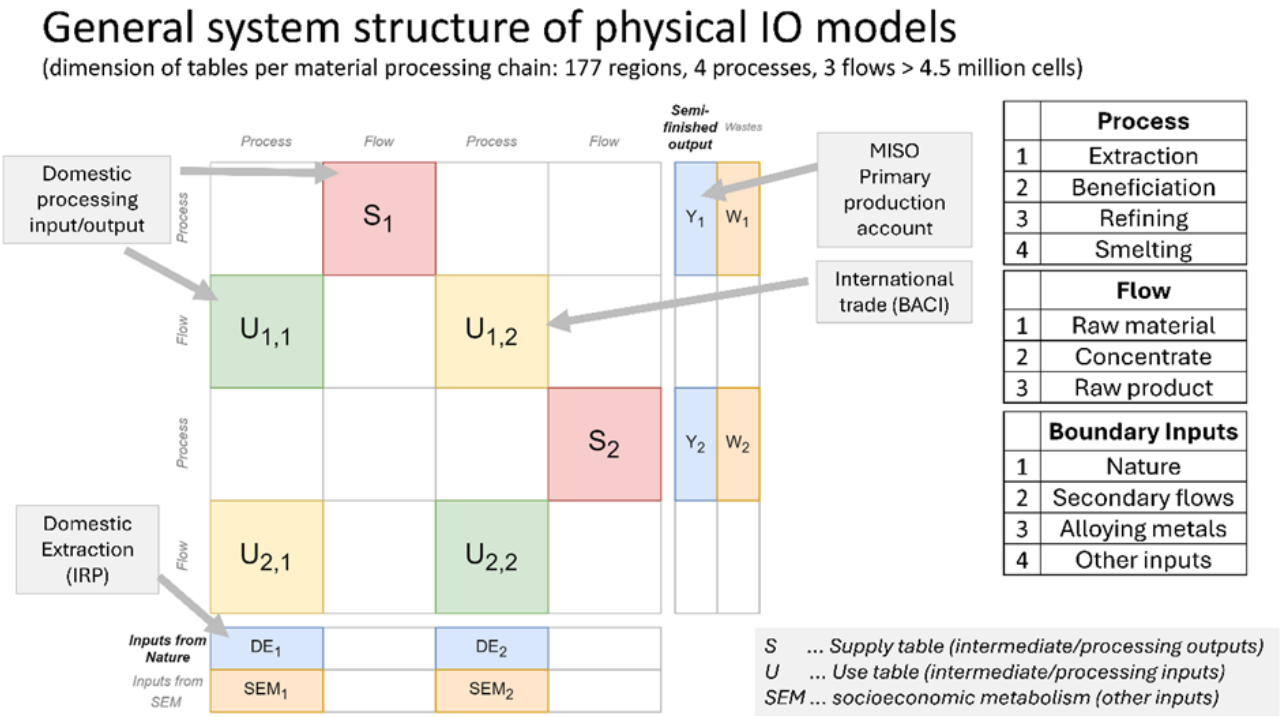


Figure 5: System structure of the multi-regional physical input-output modelling framework for stock-building material processing chains. Each of the 12 material processing chains is analyzed in a mass-balanced IO framework from raw material extraction to primary material production including all secondary flows and other inputs in units of metric tons per year. Please note that the accounts on extraction-related CO2 and energy use are not depicted here.

5.6.1 Calculating footprints with the IO-based extraction-production accounts

Footprint indicators depict environmental pressures in the upstream supply chain of a product, such as raw material extraction, extraction-related final energy use, and CO_2 emissions. They can be calculated based on the IO-based extraction-production accounts. The system boundaries of the 'production-based' footprints presented in result section 6.5 differ from those of traditional consumption-based indicators, which are normally driven by final demand (Wiedmann et al. 2015). The footprint indicators presented in this report are driven by primary material production. The raw material footprint (MF), as quantified in the context of the IO-based extraction-production accounts, quantifies the upstream raw material extraction due to primary material production in different regions (up to 177 countries). In this perspective, extracted raw materials are allocated to the region where primary material production is situated. See Table 3 for details of which raw materials extraction is associated with which primary production material.

When analysing footprints and raw materials embodied in trade (RME) (see additional figure in annex 9.5 regarding export/import from/to EU27+3), it is important to note that raw materials associated with traded primary materials (e.g. steel products such as flat or long products) or final products containing such raw materials (e.g. steel in cars), which are downstream of primary material production, are not quantified here. The production-related MF presented in this report (as well as the RME of trade) only depicts flows upstream of primary material production. Material flows in higher processed form are beyond the system boundaries of the extraction-production accounts modelled here. In this perspective, upstream raw material extraction is 'embodied' in the production of primary materials (e.g. bauxite is embodied in aluminium, and so forth).

The physical IO analysis is based on fully mass-balanced global accounts of different processes (extraction, concentration and production), which is why primary raw material extraction (**DE**) plus other inputs (**SEM**) must equal primary material production (**Y**) plus waste (**W**), across all regions and processes (see physical IO framework in Figure 5). A key table in the footprint calculation is the total requirement matrix (eq. 5):

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \qquad \textit{eq. 5}$$

containing the multipliers, which quantify the upstream process outputs **x** (e.g., extracted raw material or processed intermediates such bauxite and alumina) that are directly and indirectly required per ton of primary production of stock-building materials **y** (e.g., aluminum, eq. 6):

$$\mathbf{x} = \mathbf{L}\,\mathbf{y}\,. \qquad \textit{eq. 6}$$

Note that **I** stands for the identity matrix and to the power of minus one ($^{-1}$) indicates a matrix inversion. Extending the physical IO table with **e** , i.e., satellite account (also known as environmental extension) for the mining process (energy use and CO_2 emissions), and pre-multiplying **L** with direct intensities (eq. 7)

$$\mathbf{p} = \mathbf{e}\,\mathbf{x}^{-1} \qquad \textit{eq. 7}$$

allows estimating associated footprints **F** (for energy use, CO_2 emissions or waste flows) that are due to primary production **y** in different regions (eq. 8)

$$\mathbf{F} = \mathbf{p}\,\mathbf{L}\,\hat{\mathbf{y}} \qquad \textit{eq. 8}$$

5.7. Triangulation of waste management data from MISO2+ and Eurostat

To evaluate whether waste flow data from Eurostat can be utilised as inputs to MISO2 v1.1, we compared these data with modelled waste flows from MISO2. For this purpose, both waste indicators and material categories from statistics first had to be matched with those from MISO2 (Table 5). Eurostat reports *Waste treatment* which is composed of *Recovery* and *Disposal*. Recovery in turn is further differentiated into *Recycling*, *Backfilling*, and *Energy recovery*. In contrast, disposal refers to all waste that is neither reused, nor used for energy recovery purposes, but is instead disposed of without further societal use. Its subcategories comprise *Incineration*, *Landfill*, and *Other disposal*.

Regarding the match of material flow categories, we assumed that the sum of the MISO2 *final waste flows* (F_14_0), *recycling flows* (F_20_4a), and *downcycling flows* (F_20_4b) correspond to what Eurostat defines as *Waste treatment* (we here use the MISO2 material flow labels shown in Figure 3). Within this, the MISO2 recycling flows (F_20_4a) match Eurostat *Recycling*, while MISO2 downcycling flows (F_20_4b) only has a very limited match Eurostat *Backfilling*.

According to Eurostat, 'backfilling operation involves reclamation purposes in excavated areas or engineering purposes in landscaping, however it has to substitute other materials that are not waste' (Eurostat - Material flows 2025), and therefore should align with the MISO2 definition of downcycling. MISO2 *final waste flows* (F_14_0_waste_final) and Eurostat *Disposal* flows are not directly comparable as MISO2 generation of recoverable waste flows occurring during production and processing (from production of raw-, semi-finished- and final products, F_5_11a/b, F_7_11a/bs, and F_9_11a/b, respectively) are likely unaccounted for in Eurostat data. Eurostat does likely not account these flows as they are most probably treated within the same industry and thus do not enter waste collection, or because the waste flow is unrecoverable, meaning that it represents an actual material loss to the environment.

Regarding the match of material types between MISO2 and Eurostat, we used Eurostat definitions provided in *'Guidance on classification of waste according to EWC-Stat categories'* (Eurostat 2010) (Table 5). Many materials are directly comparable such as iron and steel, paper, wood, plastic, and container glass. For other materials, comparison is not as straightforward. For example, Eurostat summarizes non-ferrous metals into one aggregate category that includes metals such as aluminum, copper, tin, zinc, and lead. These are reported individually in MISO2. As a consequence, we used data from USGS (USGS 2025a) 2025 for comparison. Similarly, for non-metallic minerals, Eurostat reports waste data for *Mineral waste from construction and demolition activities* and for *Other mineral waste*, while individual material types such as bricks, concrete, or asphalt are reported in

MISO2. Though the sum of bricks, concrete and aggregates is not synonymous with C&D waste, a significant overlap can be assumed and we therefore compared the sum of waste flows of individual construction materials with the C&D waste flows reported by Eurostat.

Rubber and textile waste are reported in Eurostat but in MISO2 correspond to specific end-uses. However, in MISO2, tracing end-use specific waste flows beyond EOL is not possible based on the available data, making further comparisons challenging. It can nevertheless be assumed that these materials are included in total MISO2 waste flows. This is the case for rubber, mainly corresponding to vehicle tires in Eurostat, which is likely included in MISO2 plastics, as well as for textiles (polyester clothing included in MISO2 end-use textiles). Similarly, *discarded vehicles*, *discarded equipment*, *wastes containing printed circuit boards (PCB)*, *batteries and accumulators wastes* are all likely to be covered in material flows modelled in MISO2, and partly specified by MISO2 end-uses, but matching these categories is currently not possible.

Additional Eurostat categories are not comparable at all as not explicitly used in MISO2. This is the case for various chemical/dissipative categories (spent solvents, acid, alkaline or salt wastes, used oils, chemical wastes), sludges (industrial effluent sludges, sludges and liquid wastes from waste treatment, common sludges), and various agricultural and other biomass-based products without a stock-building purpose (e.g., health care and biological waste, animal and mixed food waste, vegetal wastes, animal faeces, urine and manure). However, the Eurostat category *household and similar wastes* may include materials covered in MISO2, but current groupings do not allow for matching these categories. Lastly, the waste categories *mixed and undifferentiated materials* and *sorting residues* are either not covered in MISO2 or too generic to allocate to a specific MISO2 flow. These categories were consequently not considered in comparisons with MISO2 data.

Table 5: Comparison of MISO2 and Eurostat material waste categories and assessment of their compatibility based on definitions provided in Guidance on classification of waste according to EWC-Stat categories (Eurostat 2010).

MISO2 categories	**Eurostat categories**	**Compatibility**
Final waste (F_14_0), Recycling (F_20_4a), Downcycling (F_20_4b)	Waste treatment	Comparable, although differences in coverage (e.g., processing wastes missing in Eurostat)
Recycling (F_20_4a),	Recycling	Comparable
Downcycling (F_20_4b),	Backfilling	Limited comparability (differences in materials and processes)
Processing wastes (F_5_11a, F_7_11a, F_9_11a)	–	Not comparable (largely absent in Eurostat data)
Paper	Paper and cardboard waste	Comparable
Wood	Wood waste	Comparable
Container glass	Glass waste	Comparable
Plastic	Plastic waste	Comparable
Iron & steel	Ferrous metals	Comparable
Aluminum, copper, lead, tin, chromium, zinc, nickel, manganese	Non-ferrous metals	Eurostat category is an aggregate of an undefined number of materials. Individual materials were instead compared with USGS recycling data.
Concrete, bricks, asphalt	Mineral waste from construction and demolition (C&D)	Eurostat category is an aggregate of various mineral materials. For comparison, the sum of concrete, bricks, and asphalt were used was compared with Eurostat C&D waste.
Various end-uses (vehicles, textiles, tyres, machinery)	Product-specific waste flows (e.g., discarded vehicles, textile waste, rubber waste, discarded equipment)	Not comparable at individual level (end-uses not tracked in waste treatment), but implicitly modelled in MISO2.
–	Waste flows outside of MISO2 scope (e.g., spent solvents, used oils, chemical wastes, health care and biological waste, animal waste, etc.)	Not comparable (not represented in MISO2)

6. Results

We provide an economy-wide perspective on the socio-economic metabolism of Europe and its circularity. We include all economy-wide cycles of biomass, non-metallic minerals, metals and ores, as well as fossil fuels, which we differentiate into stock-building and non-stock-building material flows (section 6.1). We assess their circularity along three indicators for narrower, slower and more closed material cycles (section 6.2). Then we zoom into the dynamics of stock-building material flows and compare modelled to reported waste flows (section 6.3), quantify related energy use and GHG emissions (section 6.4), as well as raw material extraction (section 6.5).

The scope of the presented analyses across sections differs due to data availability: Sections 6.1-6.2 show results for economy-wide material flows in the EU27 (without Norway, Switzerland, United Kingdom) and the years 2000-2022 because EU27 trade data was only available for this scope. Sections 6.3-6.4 report stock-building material dynamics, as well as related energy and GHG flows (including non-CO2 GHGs) for the EU27+3 (including Norway, Switzerland, United Kingdom; except where specified otherwise), while section 6.5 adheres to the same regional scope but does not cover glass and bricks due to data limitations.

6.1. Economy-wide material flows in the EU27 from 2000-2022

We estimate that Processed Materials (PM) in the EU27 increased from 8.2 Gt/year in 2000, to 8.9 Gt/year in 2007, and afterwards declined to 7.9 Gt/year in 2022 (7.4 Gt/yr during 2020 Covid crisis; Figure 6). Between 68-78% of these materials originated from domestic extraction within the EU27 territory, the rest coming from imports (18-21%) and recycling within the region (6-11%). Around 42-46% of PM consist of biomass and fossil fuels, the majority of which is used for energy supply, food and feed. The remaining share of PM mainly consists of non-metallic minerals and metals which account for 52-65% of the PM. The stock-building flows of these four material groups make up around 51-57% of PM — 55% in 2022, 11%-points of which from recycling. Discarded end-of-life material stocks made up 34-46% of waste flows, out of which 22-31% were recycled or downcycled. Many of the other material flows indicators stayed remarkably stable with only slight fluctuations of material use for energy (2000: 3.2 Gt/yr, 2007: 2.9 Gt/yr), as well as slightly increasing throughput (1.5 Gt/yr to 1.7 Gt/yr) and exports (0.4 Gt/yr to 0.6 Gt/yr). Only the stock additions showed more variation (from 3.1 Gt/yr over 3.4 Gt/yr to 2.7 Gt/yr), as well as waste management (2.3 Gt/yr to 3.1 Gt/yr) and related recycling flows (0.5 Gt/yr to 0.9 Gt/yr) with starker increases.

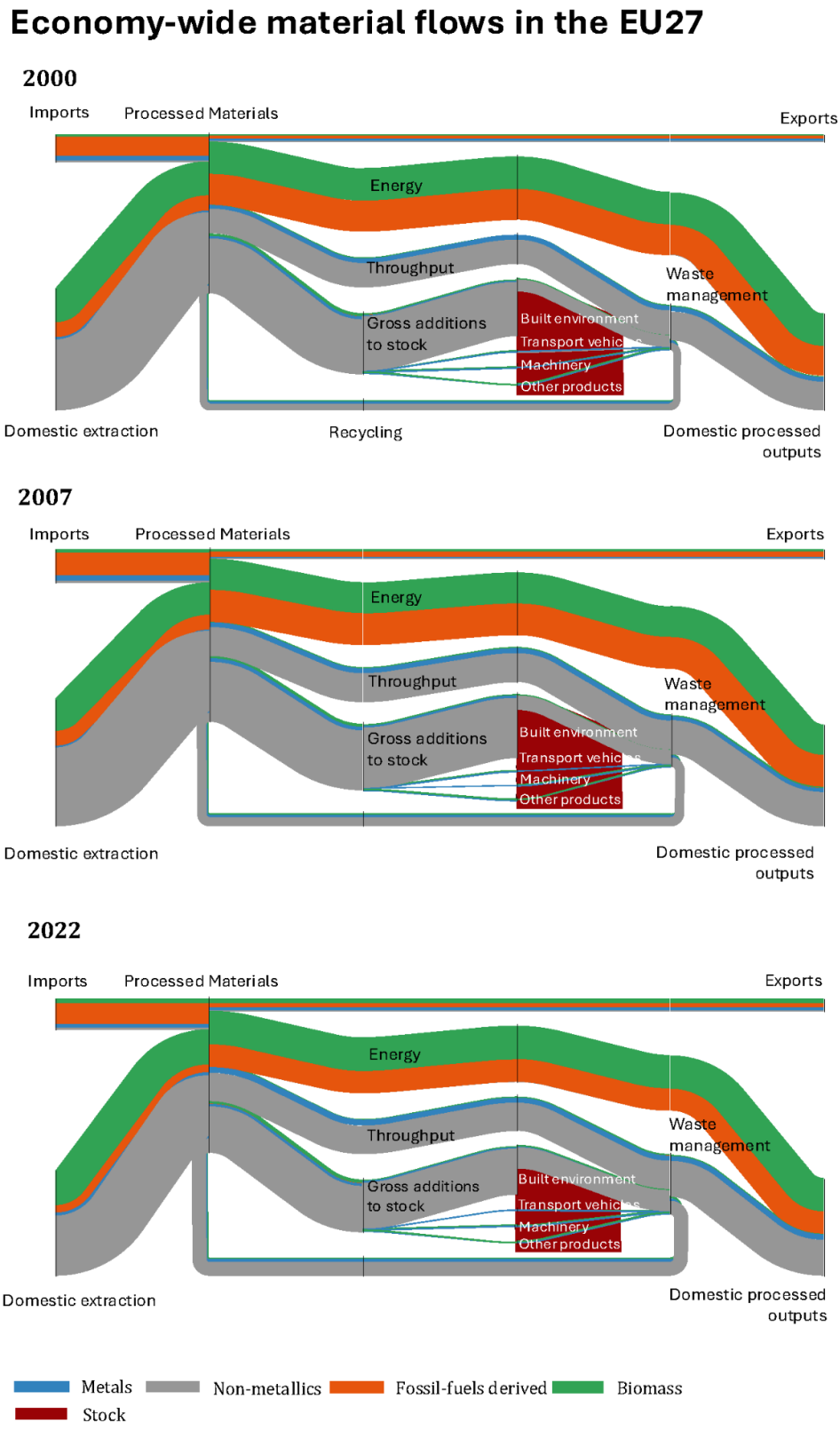


Figure 6: Economy-wide material and energy flows for the EU27, visualized as Sankey diagrams, where the width of flows corresponds to the respective flow quantities.

6.2. Economy-wide material circularity in the EU27+3

We assessed economy-wide circularity for all 27 EU+3 member states. Here we present and discuss the results for the EU27 as a whole and as examples for three individual countries (Germany, Italy and Poland); results for all other countries are available in Annex Figure 28 to Figure 30. In this chapter, we only look at the aggregate of EU27 instead of the EU27+3 countries because adequate trade data was only available for that scope (see section 5.3). To assess how countries perform in terms of narrowing, slowing and closing their material cycles we use three indicators: the temporal development of processed materials (PM/year, narrow), material retention time (MRT, slow), and the circular material use rate (CMU, close; see methods section 5.4).

6.2.1 Economy-wide material circularity in the EU27

We find that in the EU27 Processed Materials (PM/year) are slightly narrowing (declining) since 2007, as well as small improvements in the slowing (MRT) and closing (CMU) of material cycles between 2000 to 2022 (Figure 7). Annual PM grew to around 8.9 Gt/year in 2007 and slightly narrowed thereafter to 7.9 Gt/year in 2022 — a decrease of 11%. The MRT increased from 14 years in 2000, to 19.5 years in 2022 due to slowing stock growth and declining PM, indicating slowing material cycles. The CMU increased from 7% in 2000 to 12% in 2022, indicating slightly improved closing of material cycles, however with very large improvement potentials. These overall results are largely shaped by non-metallic minerals, which dominate total material stocks and flows. Individual materials show differing dynamics. For example, the CMU for metals is substantially higher (24-28%, outlier at 38%) than the rate over all materials.

In contrast, according to Eurostat estimates[2], PM grew slightly since 2010 to around 9.7 Gt/yr in 2022 — an increase of 2%. Figure 7 also shows the differences between our own calculations of PM and CMU, and the data provided by Eurostat. Differences are mainly due to detailed input data used in MISO2 and the statistical data used by Eurostat to calculate these indicators. MISO2+ uses different data sources for extraction of materials to calculate PM; this is particularly an issue with respect to the large flow of non-metallic minerals:

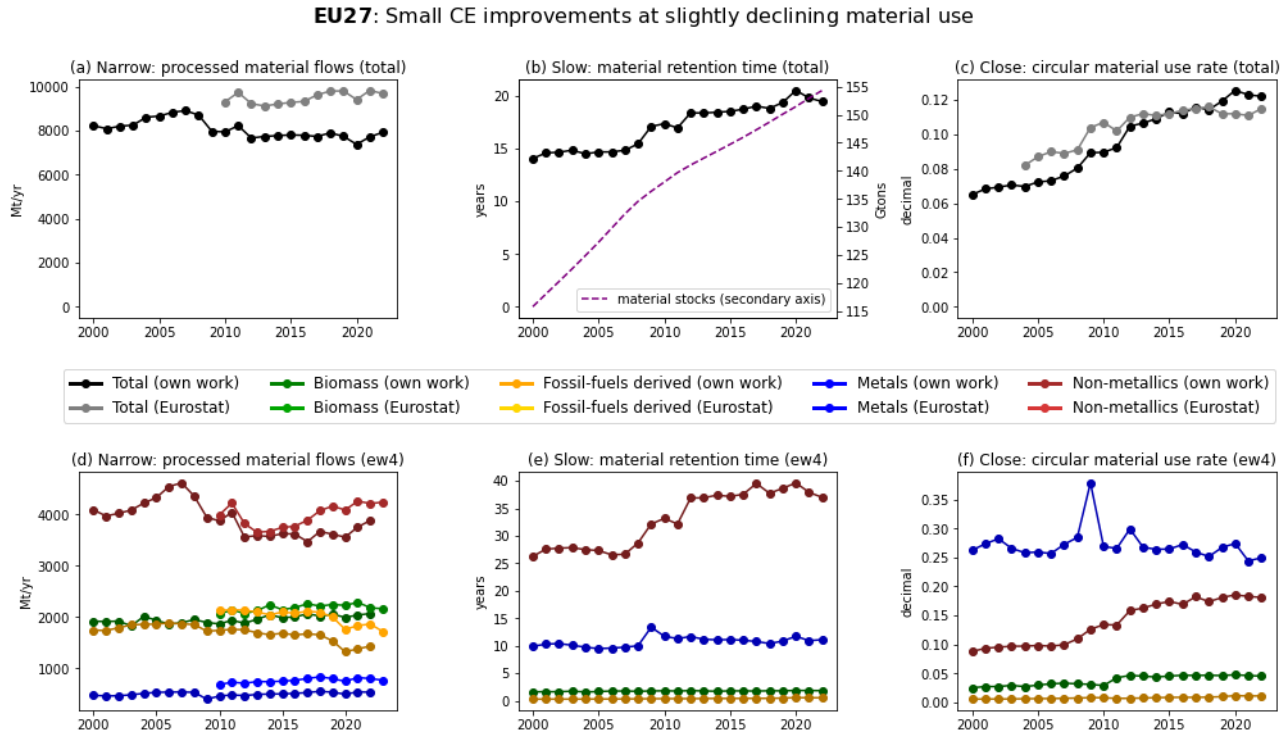


Figure 7: Temporal developments of economy-wide circularity indicators: processed materials (PM), material retention time (MRT,), and the circular material use rate (CMU) in the EU27 (see methods section 5.4 for indicator details). Comparison of results from own work with indicator values provided by Eurostat.

Eurostat uses data for sand and gravel extraction reported by national statistical offices while MISO2 uses a demand-based estimates and data sourced from the UNEP-IRP global material flow database to quantify PM. This is a large material flow, and uncertainties both for reported and estimated data are high. Considerable deviations also occur for the flows of recycled materials: Also, here Eurostat uses reported data from waste statistics, while MISO2 only partially uses absolute recycling flow data from Eurostat and USGS, and especially for non-metallic minerals relies on recycling rates from statistical sources to modelled waste flows (see section 9.1 on recycling data used in MISO2 and section 6.3.2 on comparison of reported and modelled waste flows).

Despite slightly narrowing material cycles, the level of PM in the EU27 in 2022, ranging from 17.8 tons/cap/year (own estimate) to 21.7 tons/cap/year (Eurostat), is quite high compared to a global average of 15.3 tons/cap/year (DMI from (UNEP 2025).

[2] Please note, that the Eurostat data itself differs between the downloadable raw data, and the reported indicators. Next steps therefore include collaborating with JRC and Eurostat to improve upon methodology and reporting scheme.

6.2.2 *Economy-wide material circularity in three country case studies*

In addition to looking at the circularity of the EU27, we selected three country case studies with interesting and distinct CE-dynamics: Germany, Italy and Poland.

In Germany, similar developments as for the EU27 are found, with a relatively stable PM over most years, with slightly more narrowing recently. We also find a slowing MRT at similar stock growth, but slightly higher CMU (Figure 8). The decline in PM is mainly due to reductions in the use of non-metallic minerals (construction) and fossil materials (energy transition), while material retention time increases for the former.

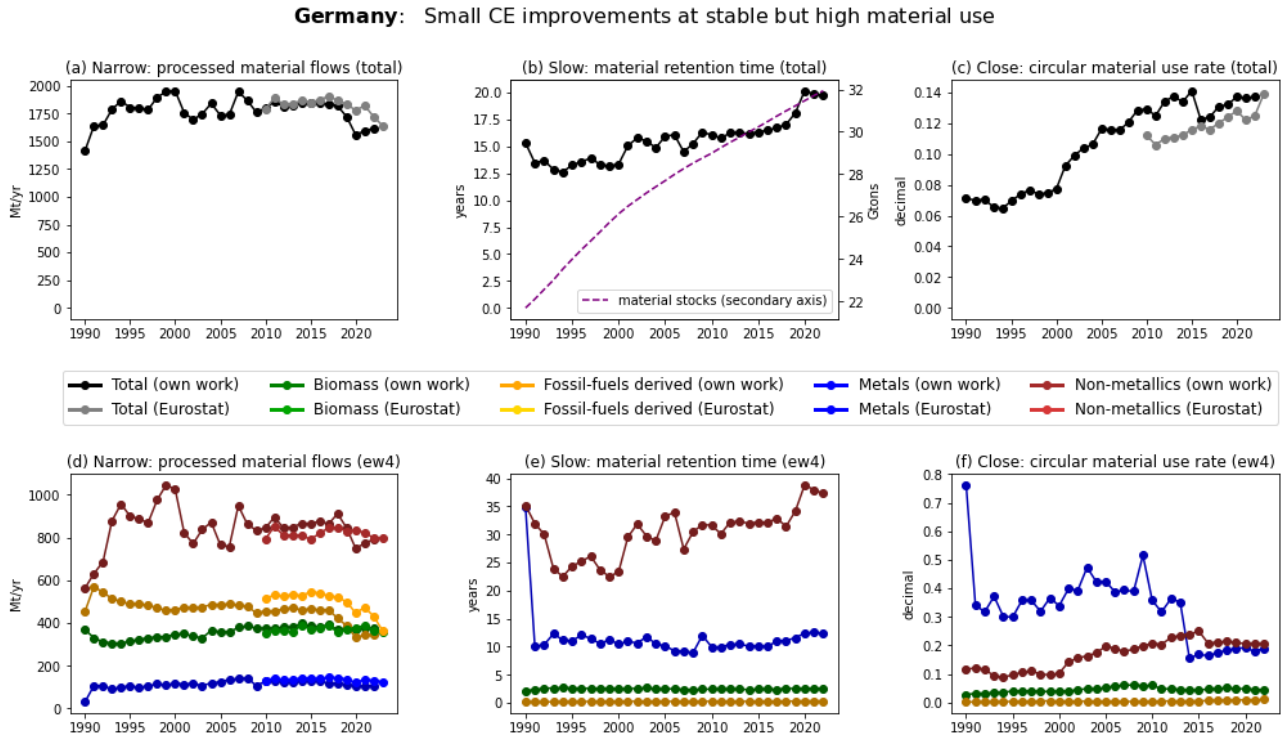


Figure 8: Temporal developments of processed materials (PM), material retention time (MRT,), and the circular material use rate (CMU) in Germany (see methods section 5.4 for indicator details). Comparison of results from own work with indicator values provided by Eurostat.

In comparison, we find much stronger improvements across the CE indicators in Italy (Figure 9). PM grew to around 1 Gt/year in 2004 and afterwards declined by between 26% (Eurostat estimate) and 40% (own estimate) in 2022. These reductions are mainly due to declining demand for non-metallic minerals, primarily from the construction sector. This is reflected in material stocks, which show indications of a potential saturation since around 2010. Together with the narrowing PM this led to more than a doubling of MRT since 1990, indicating a substantial slowing of material cycles. The

CMU more than doubled, from 8% in 1990 to almost 20% in 2022. Interestingly though, the CMU for metals has been declining after 2010.

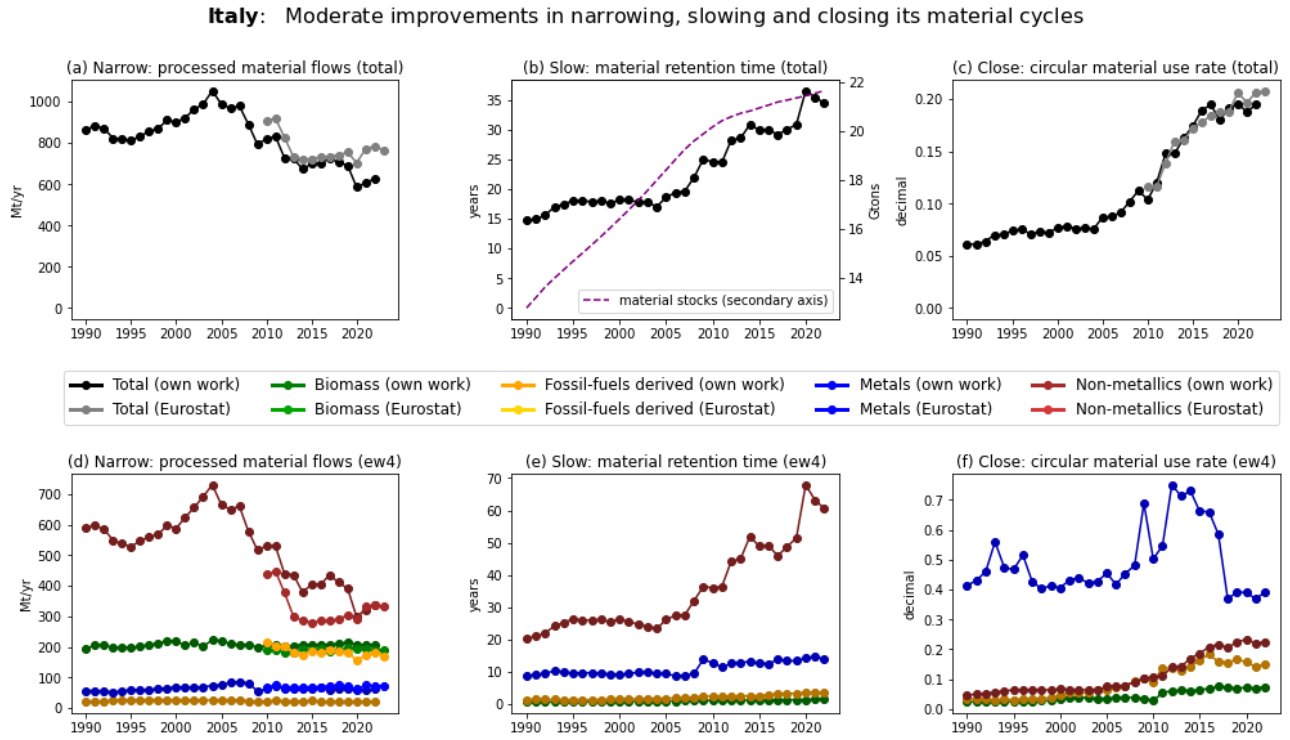


Figure 9: Temporal developments of processed materials (PM), material retention time (MRT,), and the circular material use rate (CMU) in Italy (see methods section 5.4 for indicator details). Comparison of results from own work with indicator values provided by Eurostat.

In contrast, Poland offers a completely different picture (Figure 10). We find a growing PM, strong increases of material stocks and no progress in the slowing and closing of material cycles. When using Eurostat estimates, the CMU of Poland is even declining substantially. In our estimates the PM grew from 0.7 Gt/year in 1990, to 0.9 Gt/year in 2022. This is mainly due to growing demand for non-metallic minerals and biomass, while fossil fuel - based materials declined. Growing material use in Poland was related to a build-up of material stocks, which grew strongly from 6 Gt to 10 Gt in the same period with no indications for a saturation or stabilization.

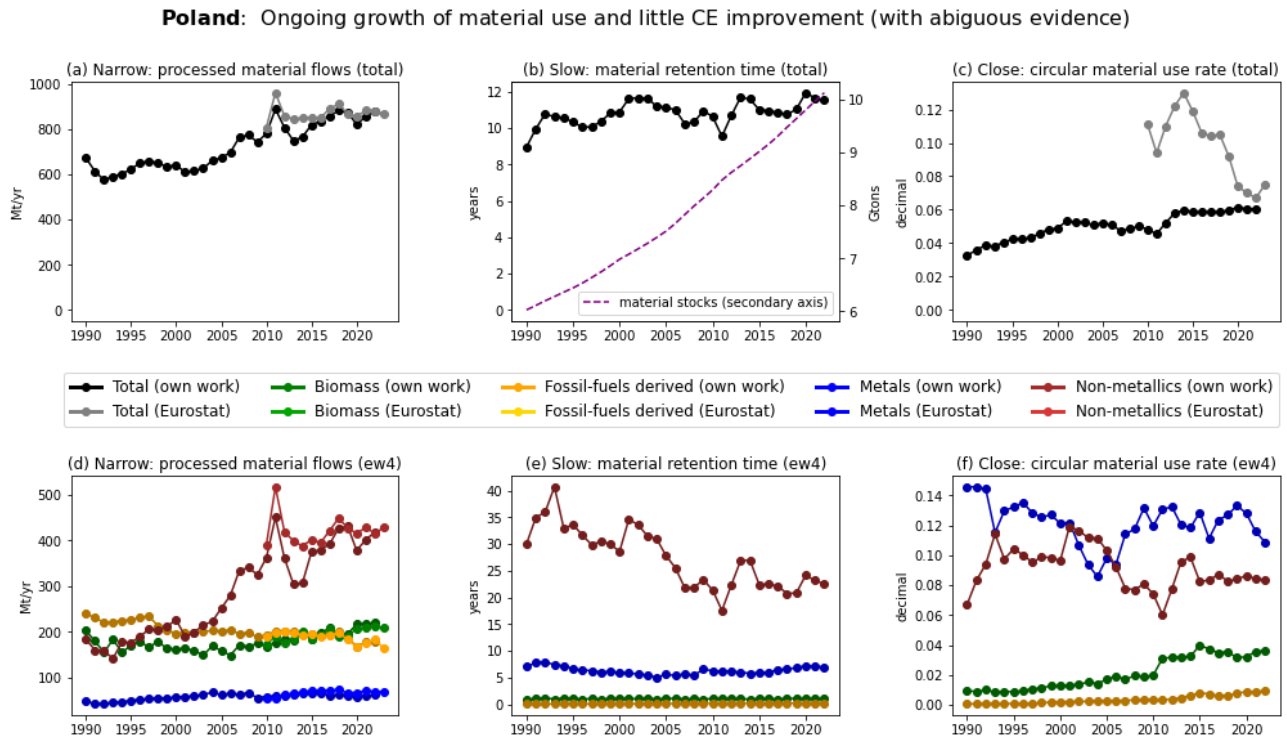


Figure 10: Temporal developments of processed materials (PM), material retention time (MRT,), and the circular material use rate (CMU) in Poland (see methods section 5.4 for indicator details).Comparison of results from own work with indicator values provided by Eurostat.

Evidence on the CMU in Poland shows strong contrast between our estimate and that of Eurostat indicating a slightly growing vs. a stronger declining trend, respectively. As the CMU is calculated as the ratio of recycling flows and DMC (PM less exports), the divergences result from mismatches of the estimates of these two flows between our modelling and the Eurostat estimate (section 5.3). For Poland, while the DMC shows relatively good alignment, the recycling flows largely differ for 2014-2018 between the two estimates (see Table 6). More specifically, we estimate recycling flows for the overlapping period from 2014 to 2022 to grow from 40 Mt/year to 50 Mt/year, while Eurostat reports recycling flows to decline from 88 Mt/year to 43 Mt/year in the same period. This difference is dominated by the material group of non-metallic minerals. The comparatively low value of our estimate stems from a substantially lower estimate of supply of recoverable mineral waste (e.g., 48 Mt/year in 2014 against 139 Mt/year from Eurostat). These discrepancies emerge from the mismatch of reported vs. modelled waste data, as well as potentially differing system boundaries as discussed in this section before.

Table 6: Comparison of indicators to calculate the CMU for Poland and data to understand discrepancies. Please note, that the Eurostat flow data extracted from the Eurostat database does not exactly reproduce the Circular Material Use Rate which is also available for download from Eurostat

Indicator/year (unit: Mtons/year)	**2014**	**2016**	**2018**	**2020**	**2022**
DMC, total (own estimate); calculated as PM - Exports	671	750	775	768	823
DMC, total (Eurostat); calculated as PM - Exports	760	756	815	757	776
Recycling and downcycling, total (own estimate)	40	44	45	47	50
Recycling, total (Eurostat)	88	73	76	45	43
Recycling and downcycling, non-metallic minerals (own estimate)	28	29	31	33	35
Recycling, non-metallic minerals (Eurostat)	64	51	53	27	26
Recoverable waste supply, non-metallic minerals (own estimate)	48	51	54	58	62
Waste treatment, non-metallic minerals (Eurostat)	139	124	119	106	111

6.3. Material stocks and related stock-building flows in the EU27+3

6.3.1 Material stocks, their additions and end-of-life outflows

This section provides a brief overview of the recent developments of material stocks and stock-building material flows in the EU27+3. Material stocks have a large influence on potentials and limitations to narrow, close and slow material loops. More than half of all materials used in the EU27 are used to build up and maintain the stock of buildings, infrastructures, vehicles, machinery and other long-lived products (see section 6.1). Those materials only become available for recycling at the end of their service lifetime.

We estimate the total material stocks in the EU27+3 at 175 Gt in 2022 (Figure 11; 154 Gt for EU27). Most of the total material stocks have accumulated in roads (60 Gt), civil engineering (49 Gt), residential buildings (36 Gt), and non-residential buildings (27 Gt) (Figure 11 a). Most of these stocks are aggregates, concrete, asphalt, as well as bricks (Figure 11 b). Machinery and short-lived products weigh two orders of magnitude less, the majority of which are machinery and equipment (0.9 Gt), motor vehicles (0.5 Gt), and other transport equipment (0.3 Gt) (Figure 11 c, d). These end-uses primarily contain metals and plastics, but also timber and paper, also including packaging materials with very short lifetimes used across the material supply chain (Figure 11 c).

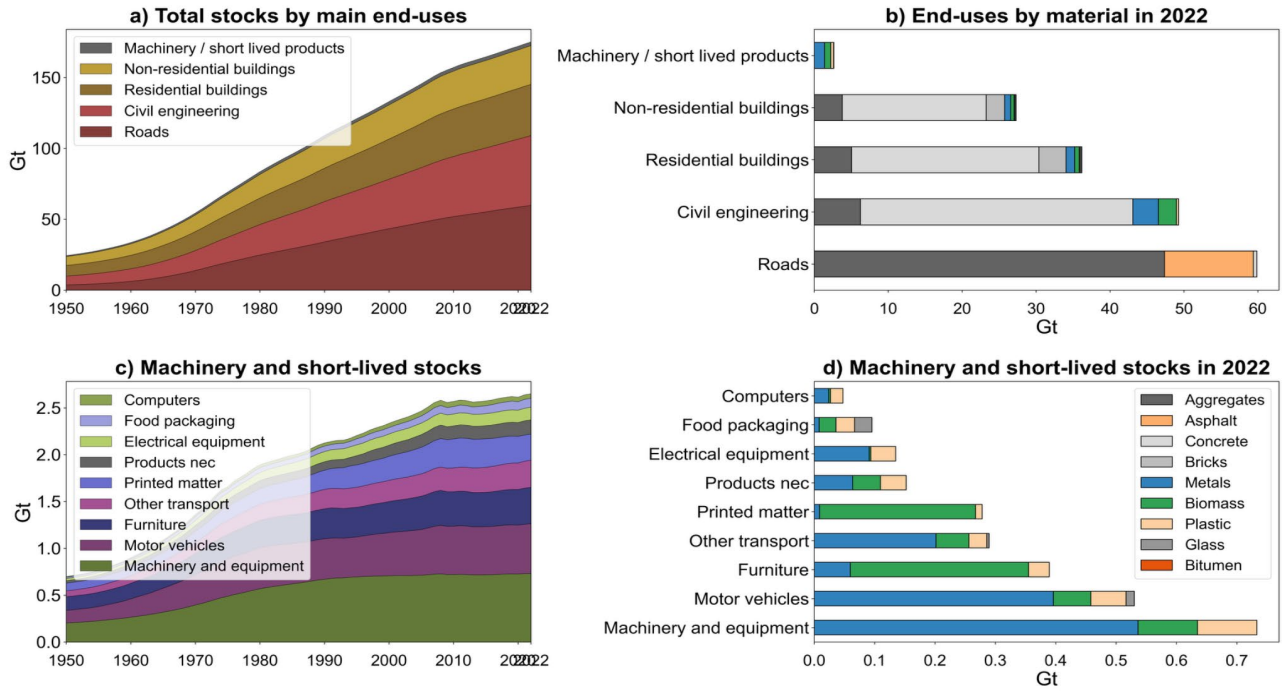


Figure 11: EU27+3 material stocks by end-use, from 1950 to 2022 (a,c), and by material for each end-use in 2022 (b,d).

Per capita, material stocks in the EU27+3 grew from 224 t/cap in 1990 to 330 t/cap in 2022 (Figure 12). Annual stock growth rates were 2.3% in the early 1990s, dropped below 1% since 2012 and were 0.85% in 2022. Overall material composition did not change significantly (could vary through changing production levels across materials or manufacturing to different end-uses) during the 32 years considered, mainly because construction techniques around steel reinforced concrete remained dominant. Concrete constitutes the largest fraction (46% in 1990 and 47% in 2022) followed by sand and gravel, summarised as "aggregates" (34% in 1970 and 36% in 2022).

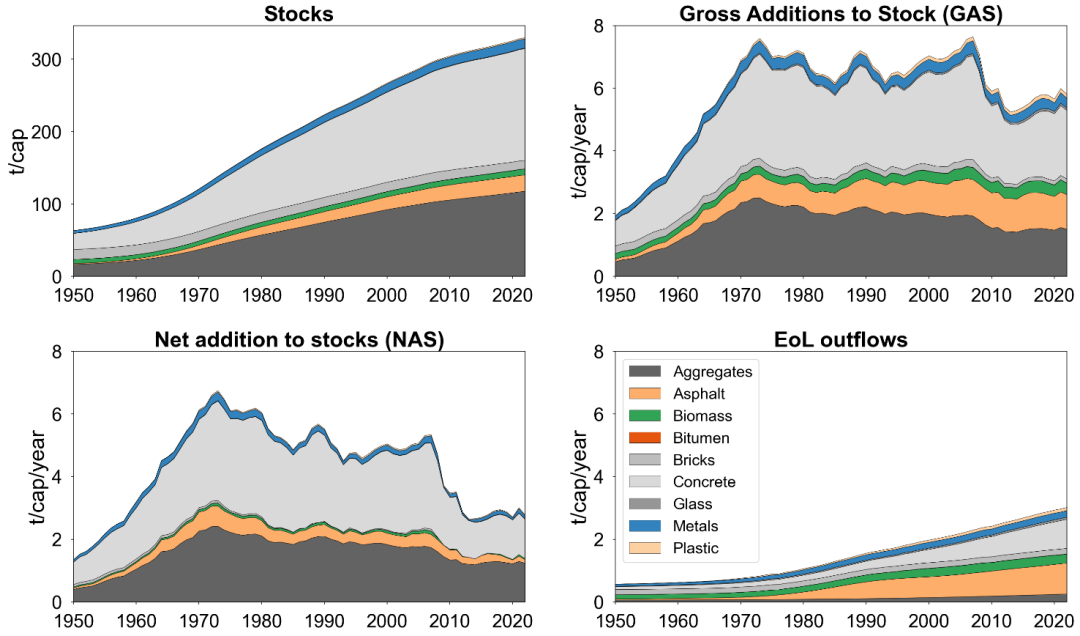


Figure 12: Development of stocks and stock-related flows in the EU27+3 between 1950 and 2022, along material groups; (a) total accumulated stocks in t/cap, (b) gross additions to stocks (GAS) in t/cap/yr, (c) net additions to stocks (NAS) in t/cap/yr, end of life outflows (EoL) in t/cap/yr. The steady increase of EoL is a characteristic time-lagged pattern going along increasing and ageing stocks.

In contrast to the steady growth of material stocks, additions to stocks followed a slightly different path, showing how stock-flow dynamics behave differently. Gross additions to stocks (GAS/yr) were relatively constant between 1970 and 2008, although with fluctuations between a maximum of 7.6 t/cap/yr in 1973 and a minimum of 6.2 t/cap/yr in 1985. Since 2008, the trend changed, with GAS/yr declining by 18%, from 7.1 t/cap/yr to 5.8 t/cap/yr in 2022 (Figure 12). The decline was observed for all bulk construction materials, but most pronounced for bricks and concrete (-30% and -28% respectively). Net additions to stocks (NAS/yr) followed a very similar trend (Figure 12) as observed for GAS/yr, with a decline from 6.8 t/cap/yr in 1973, to 5.7 t/cap/yr in 1989, and then dropping again to 2.8 t/cap/yr in 2022. Outflows from stocks, i.e., end of life wastes (EoL/yr, Figure 12) in the form of demolition and discards were constantly increasing, from 0.8 t/cap/yr to 3 t/cap/yr.

6.3.2 Comparison of modelled and reported waste and recycling flows in the EU27

Waste management and recycling helps achieve more closed material cycles. However, consistent and comprehensive data on waste and recycled flows is scarce, often incomplete and uses entirely different ontologies than resource use statistics. We here compare fully mass-balanced and stock-flow consistent modelled data from MISO2+, with reported data by Eurostat. We can only compare data for the EU27 countries, as there is not sufficient information available for the +3 countries.

Interestingly, we find relatively good agreement for total waste flows as modelled with those reported by Eurostat, but also notable differences for specific materials and over time. We compared EU27 waste treatment in 2016 from Eurostat with the sum of MISO2 material flows for final waste, recycling, and downcycling – assumed here to represent waste treated as reported by Eurostat (section 5.7). Total waste treatment flows reported for the EU27 by Eurostat amounts to ~80% of the MISO2 estimate (see Figure 13). Using Eurostat's estimate of waste generation we find a 97% match. However, at the level of individual materials and countries, the alignment shows stronger variations. For non-metallic mineral waste – primarily from construction and demolition (C&D) – Eurostat data closely match MISO2 flows, amounting to 86% of the MISO2 estimate. However, significant divergences occur for metals and biomass: Eurostat reports only 60% of the MISO2 estimate for ferrous and non-ferrous metals combined, and just 48% for biomass waste (paper, cardboard, and wood).

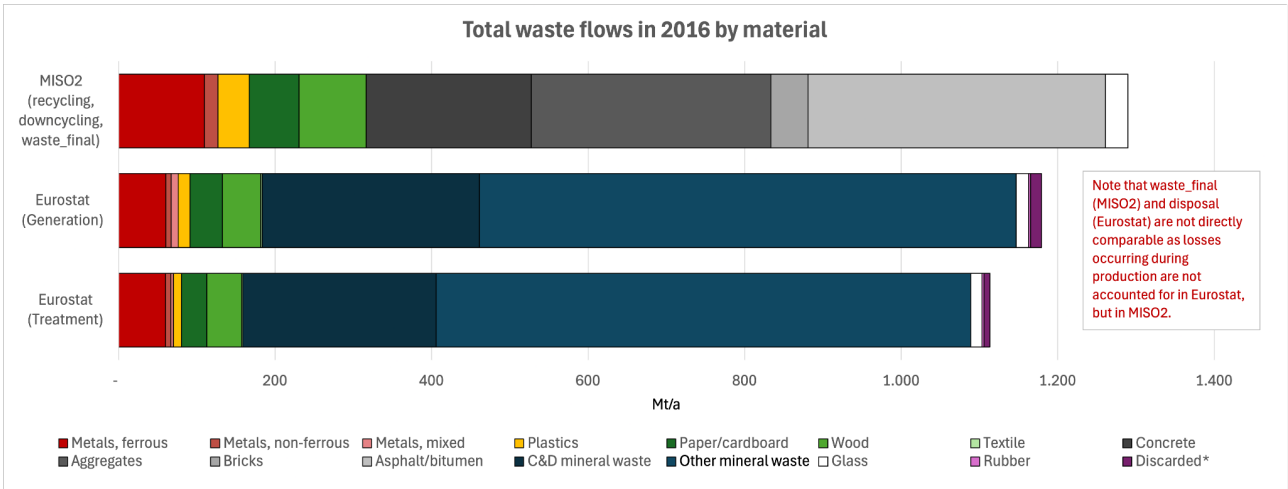


Figure 13: Comparison of MISO2 and Eurostat total waste flows. Note that all materials listed in Table 5 except for those beyond the scope of MISO2 (last row) are included in Eurostat figures.

Comparing country-level estimates for waste treatment of comparable materials for EU27 countries, we see different matching across countries (Figure 14). The best agreement in total waste treatment can be found for Malta and Poland with a percentage divergence of -19 and 27% relative to MISO2 results, respectively. For Finland and Romania, Eurostat has significantly higher estimates (398 and 307% divergence in relation to MISO2, respectively). Countries where Eurostat has significantly lower estimates compared to MISO2 are Croatia (-92%) and Slovakia (-90%). On average, Eurostat data is 8% lower than that of MISO2.

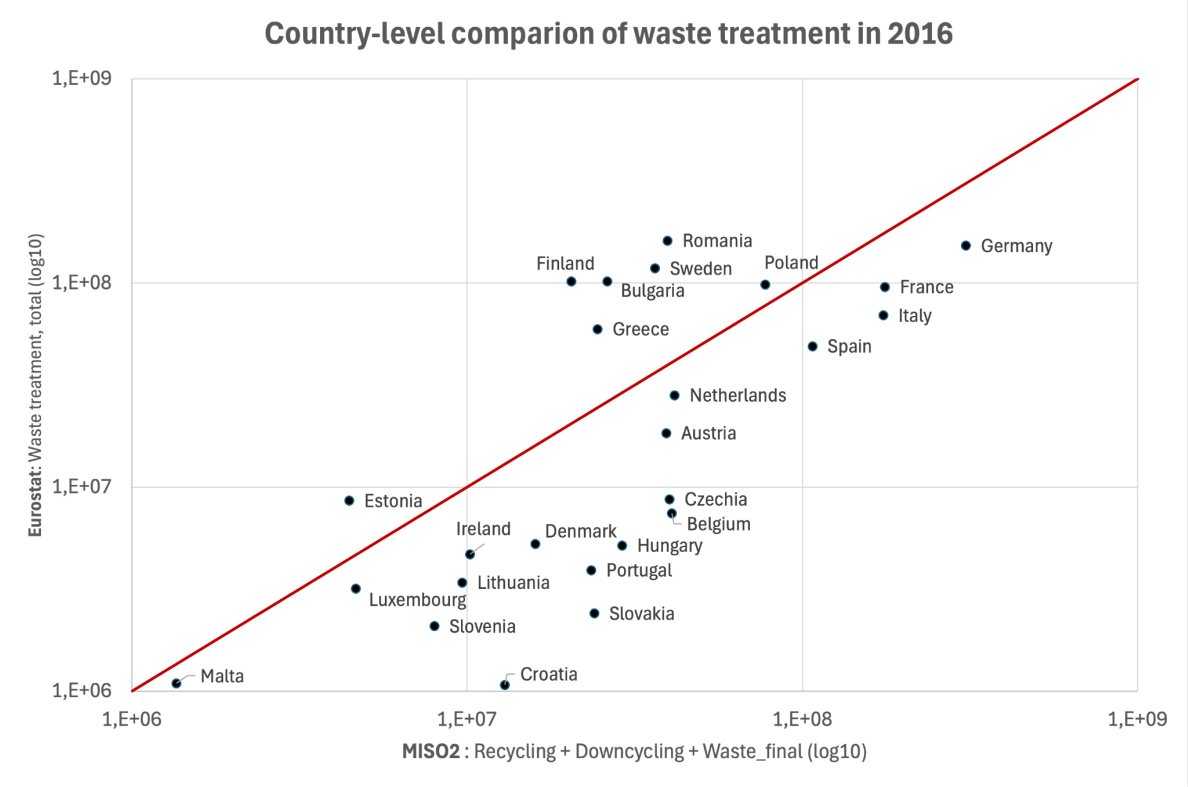


Figure 14: Country-level comparison of waste treatment in 2016 as estimated by MISO2 and reported by Eurostat, using harmonized material categories. The red line denotes equality (MISO2 value matches Eurostat value).

From a longitudinal point of view on the EU27 total waste treatment, Eurostat and MISO2 waste flows show relatively good fit. From 2010 to 2014 data matches comparably well, albeit, after that, MISO2 waste treatment increasingly surpasses Eurostat flows (see Figure 15). Meaningful comparisons over time are only possible for the years between 2010 and 2022. Before 2010, Eurostat does not report waste indicators for several material categories or end-uses. For example, bi-annual waste treatment data from 2004 to 2008 does not include metals, discarded equipment, discarded vehicles, batteries and accumulators' wastes, and mineral wastes. Consequently, Eurostat-reported waste treatment for this early time period is significantly lower than MISO2 results.

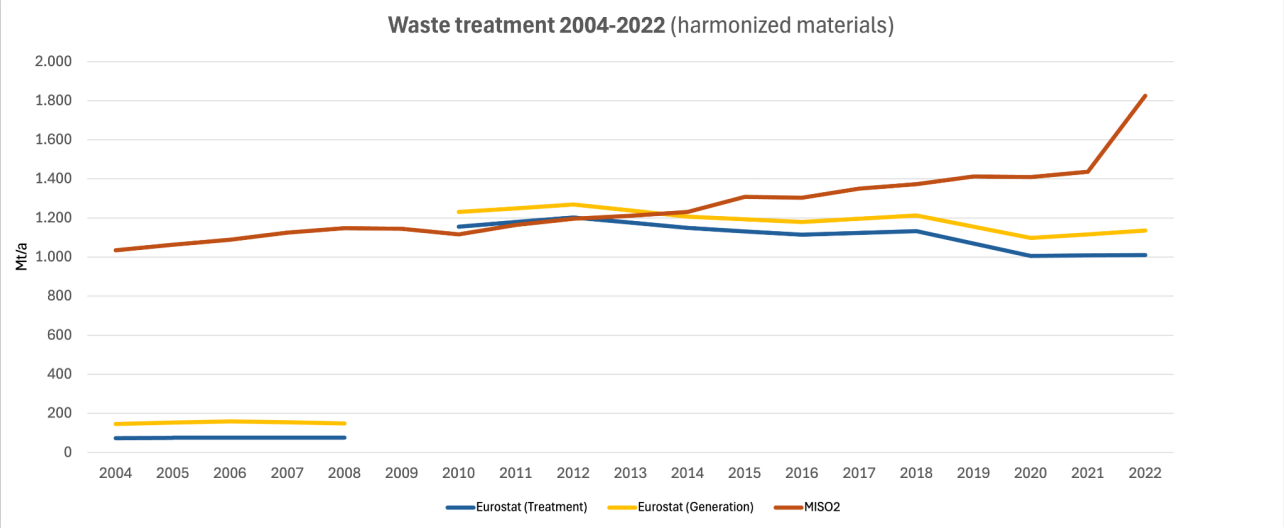


Figure 15: Comparison of waste treatment in the EU27 from 2004 to 2022. For MISO2, waste treatment corresponds to the sum of the flows recycling (F_20_4a), downcycling (F_20_4b), and final waste (F_14_0). Note that Eurostat data before 2010 does not include various material categories including metals and mineral waste (C&D). For Eurostat, values for uneven years are interpolated.

Comparing the fate of waste flows between Eurostat and MISO2 for the EU27 total (Figure 16), we observe moderate differences between the two estimates, with exception for backfilling/downcycling. Backfilling and downcycling are estimated differently in MISO2 than by Eurostat, due to different system boundary choices regarding included materials and processes. In MISO2, final waste estimates (unused wastes; i.e., waste not re- or downcycled) accounts for 39% of total waste flows, while the corresponding share in Eurostat is 56% (landfill, incineration, and other disposal) (see Figure 26). For used waste flows, in MISO2 it is estimated that 73% of used materials are recycled while the remainder is downcycled (asphalt and concrete downcycling). The Eurostat estimate reports the share of recycling in total used waste flows to be 84%, with 11% being backfilled and 6% being used for energy recovery, a category not included in MISO2.

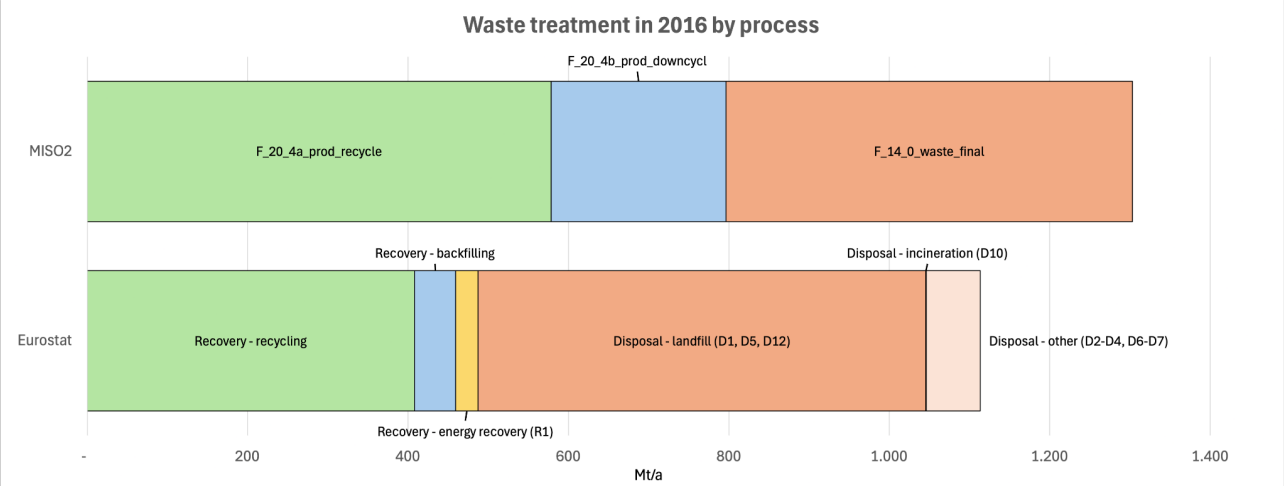


Figure 16: Absolute waste treatment flows in the EU27 in 2016 by final fate.

Differences between MISO2 model results v1.1 and Eurostat data are due to mismatches between reporting practices and data quality across countries versus consistently modelled data, as well as differing system definitions with varying completeness of coverage. The Eurostat's waste accounts provide detailed information on waste flows reported by member countries. However, Eurostat only compiles and harmonizes data as reported by the member states, which in turn have different data gathering approaches and use different sources and procedures. The Eurostat accounts so far remain disconnected from other material flow accounts such as material extraction, production processes, and additions to stocks. In contrast, the MISO2 model consistently quantifies economy-wide stock-building material flows from their extraction over processing to use and disposal and recycling. This approach establishes explicit linkages across all material flows within the socioeconomic system, most importantly connecting inputs with corresponding outputs. Finally, MISO2 explicitly models new scrap generated during production stages, while Eurostat relies on reported data where it can be assumed that significant waste flows are not reported if they are reused within industries. Consequently, such data would be absent from national and EU level statistics.

6.4. Direct energy and GHG flows associated with material stocks and flows in the EU27+3

This section describes the *direct* energy use and GHG emissions associated with the production of *stock-building* materials in the EU27+3 and contextualizes them in relation to overall fossil-fuel-related energy use and GHG emissions in the EU27+3.

To put the energy use and GHG emissions covered in here into perspective, a comparison to IEA industrial and operational energy use shows that from 1990 to 2022 operational energy use (i.e., the energy required to use and operate material stocks in the sectors residential, transport, services), exceeded industrial use by one quarter to half (Figure 17). Over this period, industrial energy use (here including agriculture, forestry and fishing) decreased by 33%, while related emissions halved. Operational energy use increased by 10%, though its emissions still dropped by 16%. In 2022 industrial energy use made up 36% and 33% of overall energy use and GHG emissions, respectively.

In relation to total industrial energy use (incl. agriculture and fishing) reported by the IEA, the material flows and processes covered in MISO2+ account for 84% of industrial energy use in 1990 and 78% in 2020. For GHG emissions, coverage ranged from 79% in 1990 to 73% in 2020 (Figure 18, red line). The share not covered—primarily attributable to the agriculture and food sector—remained relatively stable, even during crisis years such as 2009 and 2019.

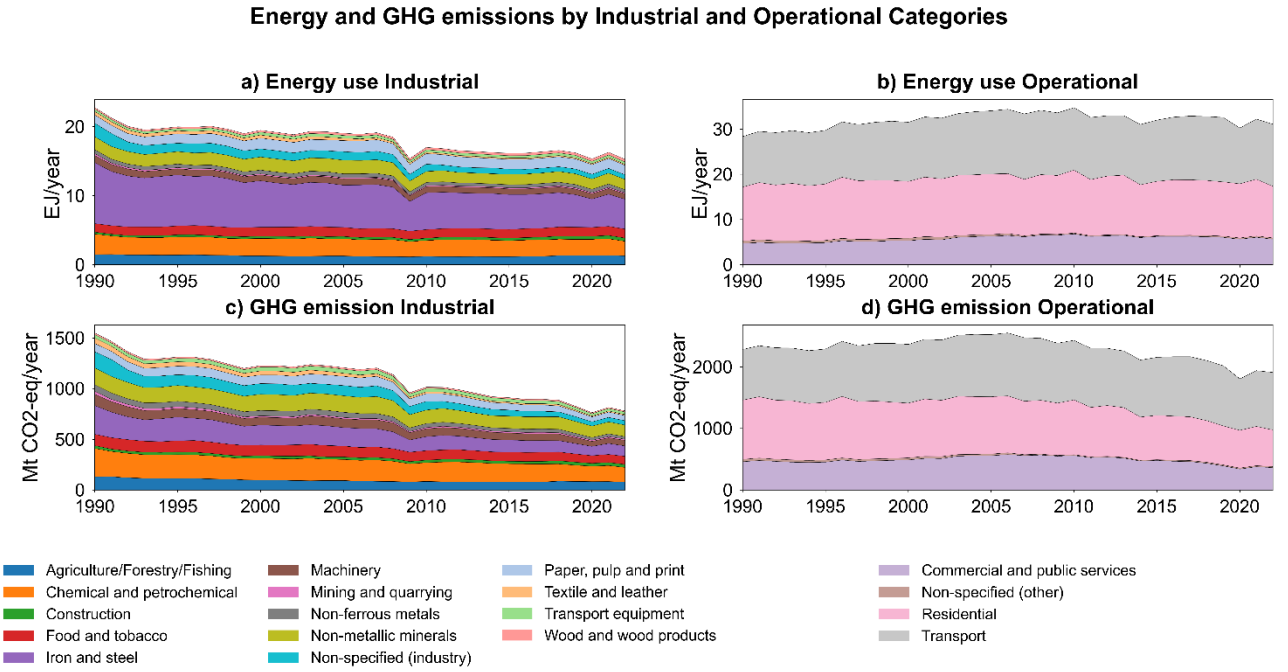


Figure 17: Industrial and operational energy consumption (EJ/year) and GHG emissions (Mt CO_2/year) from fossil fuel combustion in EU27+3 countries, 1990 to 2022 (IEA 2025a, 2025b).

Energy use and GHG emissions related to MISO2+ stock-building material flows declined by 37% and 53% from 1990 to 2022 respectively (Figure 18). In 2022, refining and smelting to raw products (MISO2 process P3 in Figure 18) made the largest contribution to both MISO2+ energy use and GHG emissions, with 6.3 EJ/year (52%) and 247 Mt CO_2-eq/year (43%), in 2022 respectively. Fabricating semi-finished products (P5) required 2.7 EJ/year (20%) and was responsible for 107 Mt CO_2-eq/year (18%). Manufacturing of final products (P7) accounted for 1.4 EJ/year (11%) and 99 Mt CO_2-eq/year (17%). Recycling and down-cycling (P13) consumed 1.0 EJ/year (8%) and emitted 79 Mt CO_2-eq/year (13%). Construction (P9) required 0.5 EJ/year (4%) and 30 Mt CO_2-eq/year (5%), while the extraction of raw materials (P1) represented the smallest share with 0.2 EJ/year (2%) and 16 Mt CO_2-eq/year (3%). Construction and recycling were the only processes that showed increases in both energy use and GHG emissions between 1990 and 2022 (+66% and +24% for energy use, and +13% and +5% for GHG emissions, respectively). Per capita, the contribution of each process and the temporal trend looks very similar (Figure 27).

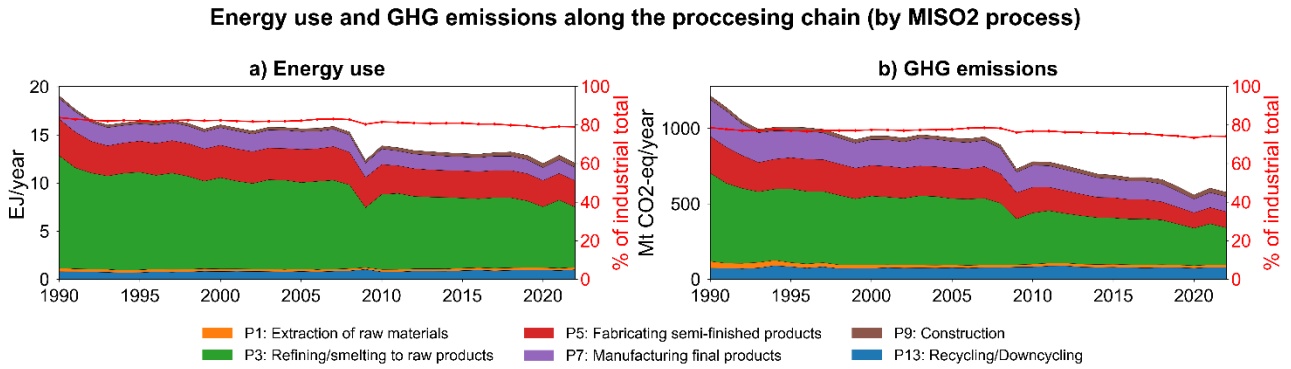


Figure 18: a) Energy consumption (EJ/year) and b) GHG emissions (Mt CO2-eq/year) by MISO process and coverage share of total industrial energy use in EU27+3 countries, 1990 to 2022. Red line gives the share of industrial energy use and GHG emissions, covered for MISO2+ stock-building materials in here, in relation to IEA industrial energy use (here including agriculture, forestry and fishing) reported by the IEA (see Figure 17).

During the extraction of raw materials (P1, 2% of energy use in Figure 18), the largest share of energy use was due to sand and gravel mining, accounting for 30% in 1990 and 32% in 2022, corresponding to 109 and 74 PJ/year, respectively (Figure 19). The related GHG emissions were 11.1/year Mt CO_2-eq in 1990 and 5.0 Mt CO_2-eq/year in 2022. As comparison, by 1990, emissions from oil and gas extraction were nearly triple at 14.4 Mt CO_2-eq/year, but decreased substantially to 3.4 Mt CO_2-eq/year in 2022. Energy use for silver extraction declined from 63 PJ/year in 1990 to 37 PJ/year in

2022, representing 18% and 16% of total energy use in P1, respectively. Timber harvesting accounted for 7% of P1 energy use in 1990 and 15% in 2022, with absolute values rising from 25 to 34 PJ/year. In contrast, GHG emissions from timber harvesting remained nearly constant, at 1.8 Mt CO_2-eq/year

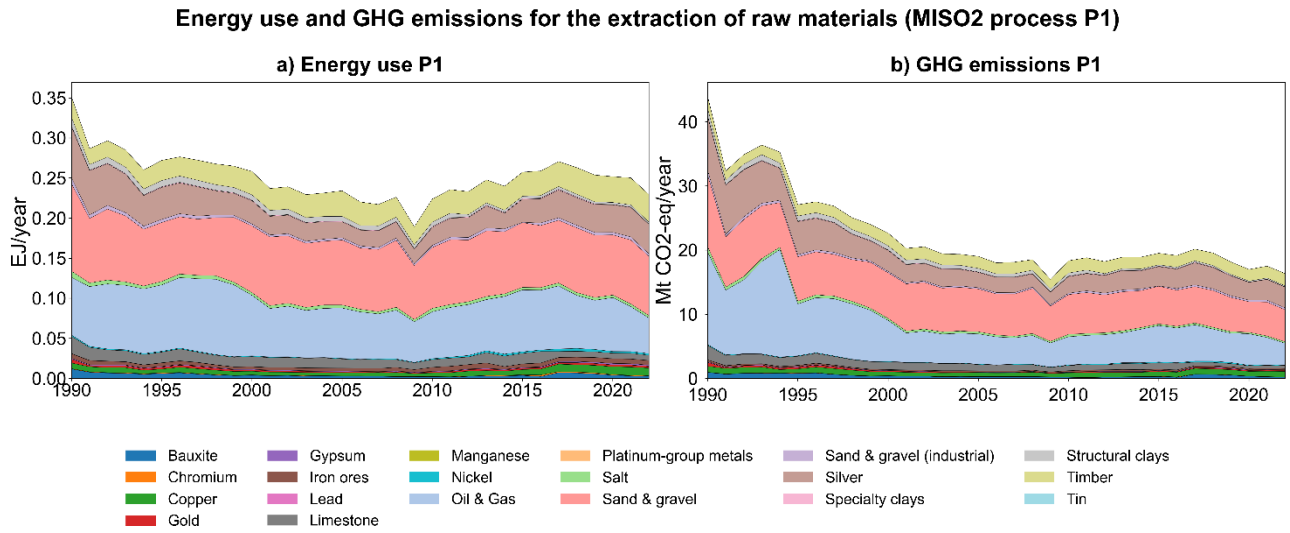


Figure 19:a) Energy consumption (EJ/yr) and b) GHG emissions (Mt CO_2-eq/year) by material in P1: extraction of raw materials in EU27+3 countries, 1990 to 2022.

in 1990 and 1.9 Mt CO_2-eq/year in 2022 (although only covering energy use related emissions, excluding land use change impacts).

Within the processing step *refining/smelting to raw products* (P3, 52% of energy use in Figure 18), the three materials iron and steel, plastics, and cement accounted for 84% of the energy use in 1990 and in 2022 (Figure 20a,b). Steel production had the highest absolute values but also achieved the largest reduction in energy use, from 7.5 EJ/year to 3.3 EJ/year (−56%) between 1990 and 2022. Primary plastic production consumed 2.0 EJ/year in 1990 and 1.3 EJ/year in 2022 (−34%). Cement production declined from 1.0 EJ/ year in 1990 to 0.7 EJ/year in 2022 (−35%). Aluminium accounted for only 2% of P3 energy use within the EU27+3. Brick production represented just 4% of energy use in 2022 (0.3 EJ/year), but contributed 8% of GHG emissions (19 MtCO_2-eq/year). Energy used for copper production increased the most in relative terms (+82%) between 1990 and 2022, although on a comparatively small scale (from 18.9 to 34.5 PJ/year).

Within the processing step *fabricating semi-finished products* (P5, 20% of energy use in Figure 18) the largest energy user in 2022 was paper production, which consumed 1.1 EJ/year — an increase from 0.9 EJ/year in 1990 (+17%; Figure 18 and d). Wood was the only other material to show an

increase, rising from 0.2 EJ/year to 0.35 EJ/year (+75%). For all other materials, energy demand declined. GHG emissions decreased across all materials in P5, leading to an overall emission reduction of 56%.

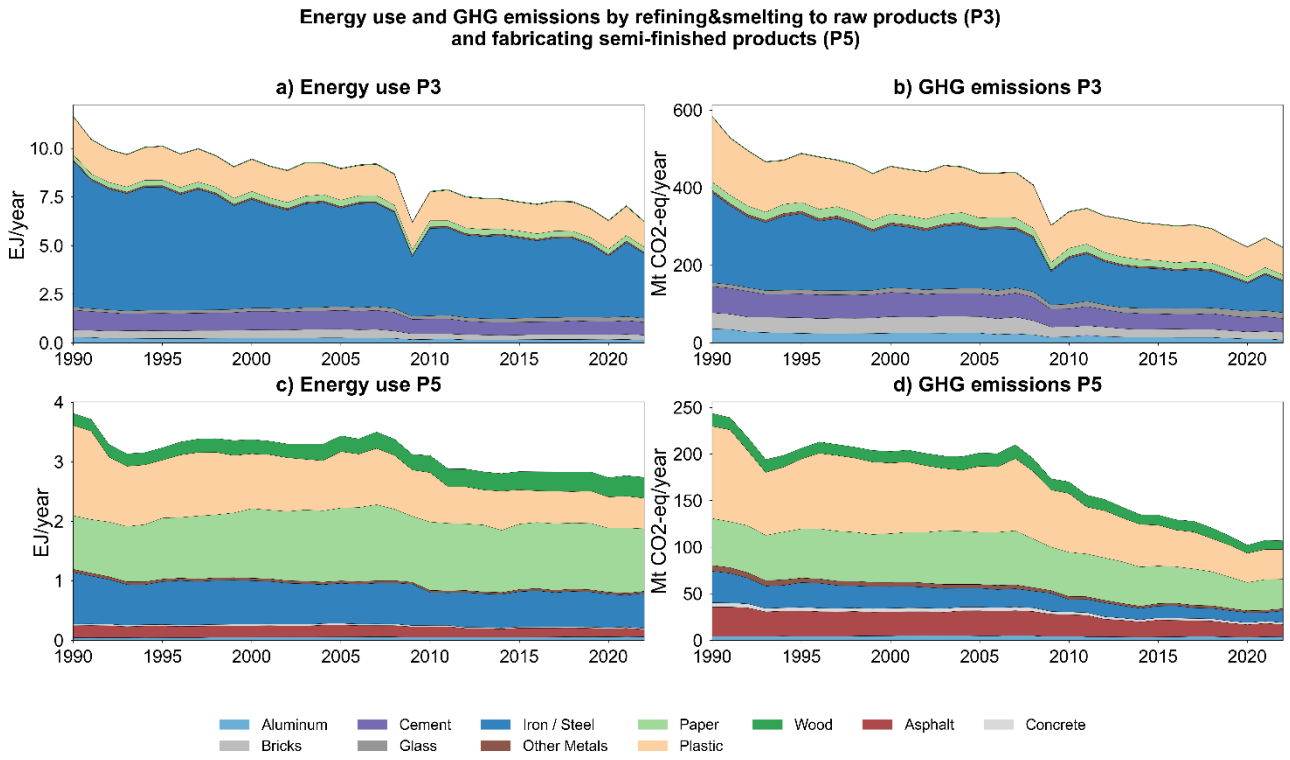


Figure 20: Energy consumption (EJ/year) and GHG emissions (Mt CO2-eq/year) by material in MISO2 processes P3 and P5: Refining/smelting to raw products in EU27+3 countries, 1990 to 2022.

Within the processing step *production of final products* (P7, 11% of energy use in Figure 18), the main energy-consuming category was machinery and equipment (e.g., washing machines, refrigerators), accounting for 33% of energy use in 1990 and 36% in 2022, corresponding to 0.7 EJ/year and 0.5 EJ/year, (Figure 21a and b). Energy use for the production of computers (0.22 EJ/year), motor vehicles (0.20 EJ/year), and other transport equipment (0.13 EJ/year) remained approximately constant, while energy demand decreased for all other product categories. The production of final products reduced its emission of GHGs by between 22% (motor vehicles) and up to 90% (Furniture) depending on final product group.

Within the processing step *construction and assembly* (P9), the construction of residential and non-residential buildings dominated energy use (Figure 21c and d), accounting for 81% in 1990 and 78% in 2022. Energy demand for the construction of residential buildings increased from 0.11 EJ/year to 0.16 EJ/year, and for non-residential buildings from 0.11 EJ/year to 0.20 EJ/year. In contrast, civil

engineering and road construction each required 0.05 EJ/year in 2022, but their relative growth since 1990 was higher than for buildings (+84% and +91% vs. +77% and +46%). GHG emissions associated with civil engineering and road construction did not increase despite higher energy

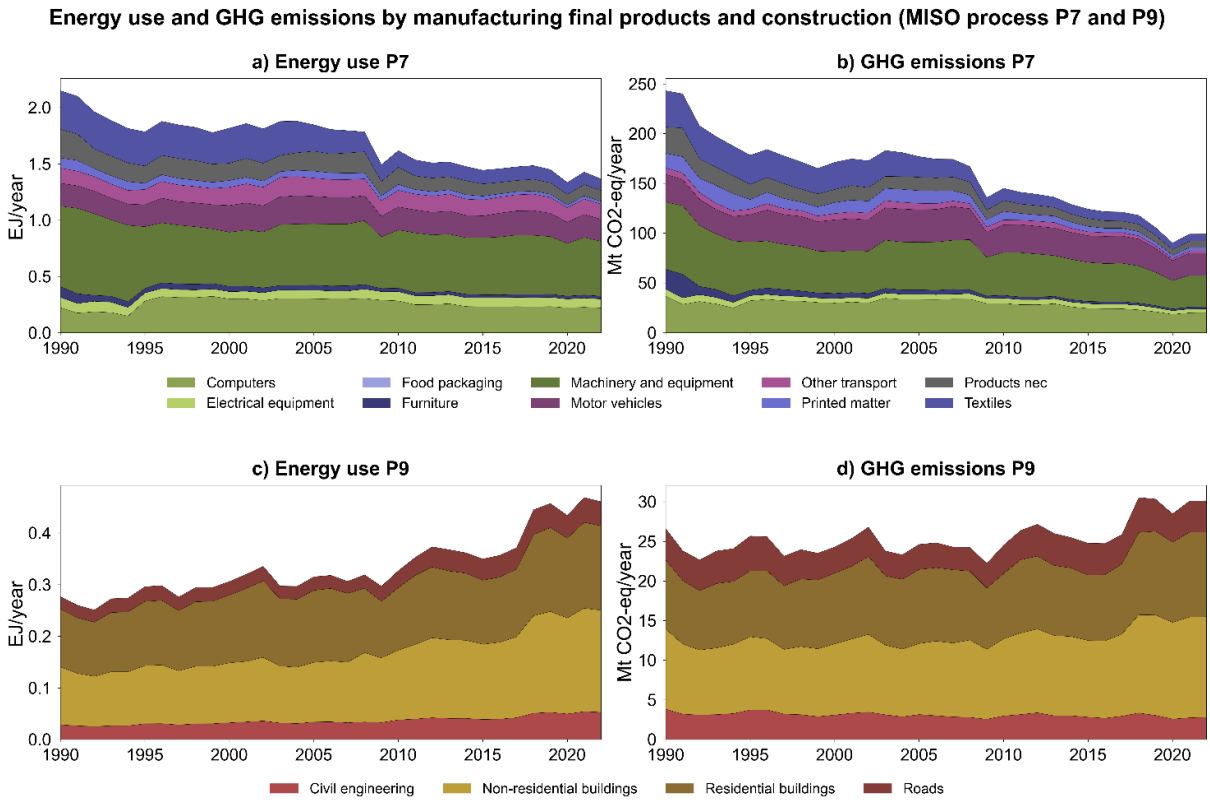


Figure 21:Energy consumption (EJ/yr) and GHG emissions (Mt CO2-eq/yr) by material in MISO processes P7 and P9: Manufacturing final products and construction in EU27+3 countries, 1990 to 2022.

consumption, whereas emissions from building construction rose by 24%—from 10.1 to 12.7 $MtCO_2$-eq/year for non-residential buildings and from 8.7 to 10.7 $MtCO_2$-eq/year for residential buildings.

Within the processing step *recycling* (P13, 8% of energy use in Figure 18), iron and steel, plastic and container glass recycling were the main energy-consuming processes in 2022, accounting for 41%, 18%, and 17% of the energy use of P13, respectively (Figure 22). Container glass showed the largest relative increase (+130%), rising from 0.07 EJ/year in 1990 to 0.17 EJ/year in 2022. Energy consumption for plastic recycling increased by 71%, from 0.10 EJ/year to 0.18 EJ/year. Energy use for steel recycling decreased by 9%, from 0.45 EJ/year to 0.41 EJ/year. Plastic recycling contributed the most to GHG emissions in P13, with a stable share of 37%, corresponding to 26.1 $MtCO_2$-eq/year in 1990 and 28.9 $MtCO_2$-eq/year in 2022. The re-/downcycling of aggregates (virgin + downcycled)

accounted for 5% of P13 energy use but 16% of P13 GHG emissions, highlighting the emission-intensive nature of energy inputs (mainly diesel) in the recycling process of this material type.

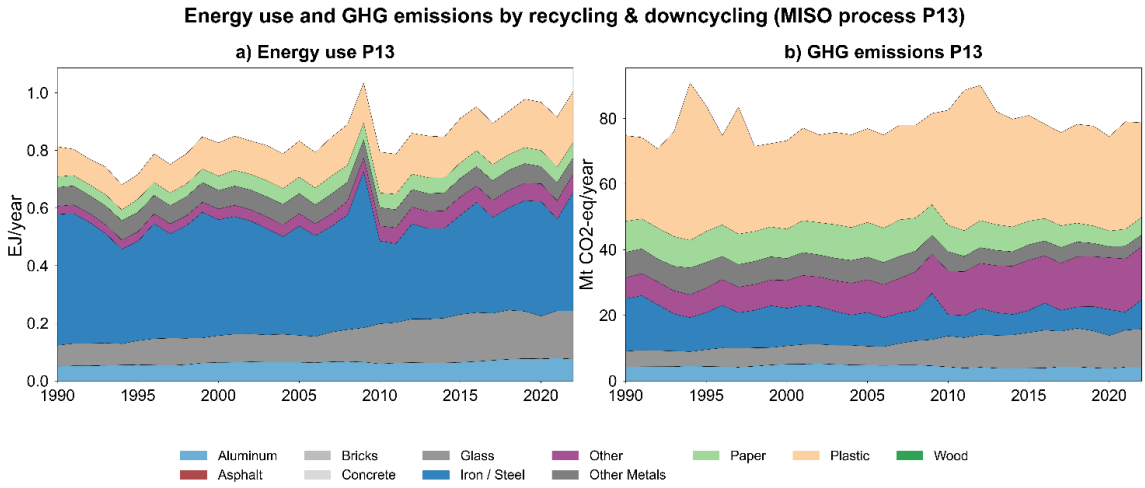


Figure 22: Energy consumption (EJ/yr) and GHG emissions (Mt CO2-eq/yr) by material in MISO process P13: Recycling & downcycling in EU27+3 countries, 1990 to 2022.

In summary, when adding up the energy use and GHG emissions across the processes of refining, fabricating and recycling materials (P3-P5-P13 which together make up 80% of energy use in Figure 18), it becomes apparent that iron and steel (43% of energy use, 23% of GHG emissions in 2022) and plastics (20% of energy use, 30% of GHG emissions in 2022) are the sectors with the largest environmental pressures (Figure 23). The overall declining trend of energy use and GHG emissions from 1990 to 2022 can be partially explained by slightly decreasing overall production since 2007, as well as shifts from primary to secondary production of raw products which is more energy efficient than primary production.

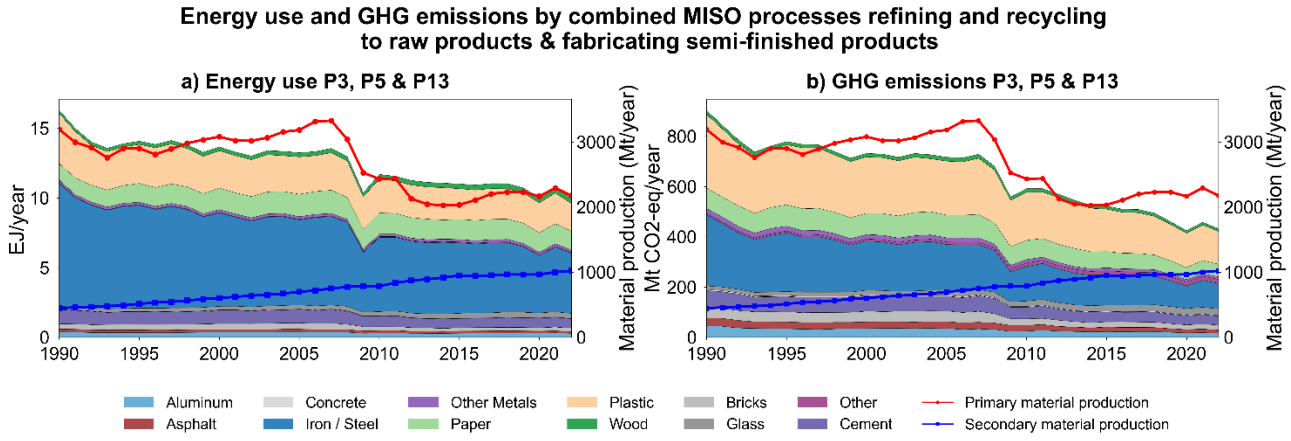


Figure 23: Energy consumption (EJ/yr) and GHG emissions (Mt CO2-eq/yr) by material as sum of MISO processes P3, P5 and P13 in EU27+3 countries, 1990 to 2022.

6.5. Carbon, energy and material footprints of stock-building materials' production in the EU27+3

This section presents an analysis of the extraction-production accounts that were constructed to link the global stock-flow model MISO2 to global raw material extraction and associated upstream energy use and CO2 emissions. For this analysis, we constructed physical input-output (IO) models which depict the material supply chain along the extraction of raw materials, raw material processing and primary production. For 2022, these models cover 38 Gt/year (71% of the total stock-building DE) of stock-building raw materials, which are ultimately responsible for the emission of 285 MtCO2/year (66% of all the stock-building extraction-related CO2) of stock-building extraction-related emissions and 2.9 EJ/year (68%) of stock-building extraction-related final energy use. We present footprint indicators for primary material production, which quantify upstream raw material extraction and extraction-related energy use and CO2 emissions embodied in production activities in the EU27+3. The aim of the footprint analysis is to quantify import flows and reveal trade dependencies and leakage effects that are associated with stock-building primary material production in the EU27+3.

In terms of methodological advancements of MEFA-based ew-CE assessments, we investigated the utility of the selected raw data sources for the envisaged purpose by means of triangulation. The logic here is that if there are substantial data conflicts between raw data sources, these are made visible through implausible results and general difficulties in the balancing run using RAS (see section 5.6).

6.5.1 Material footprints and other MFA indicators of material production in EU27+3

Figure 24 depicts the material flow indicators related to stock-building material production in the EU27+3 in 2022. The raw material footprint (MF) indicator quantifies the upstream raw material extraction related to primary material production (PMP, Process P3 in MISO2 system definition Figure 3) in the EU27+3. Secondary material production (SMP) - corresponding to MISO2 recycling and downcycling flows - and DE are shown to better contextualize and interpret PMP and MF results.

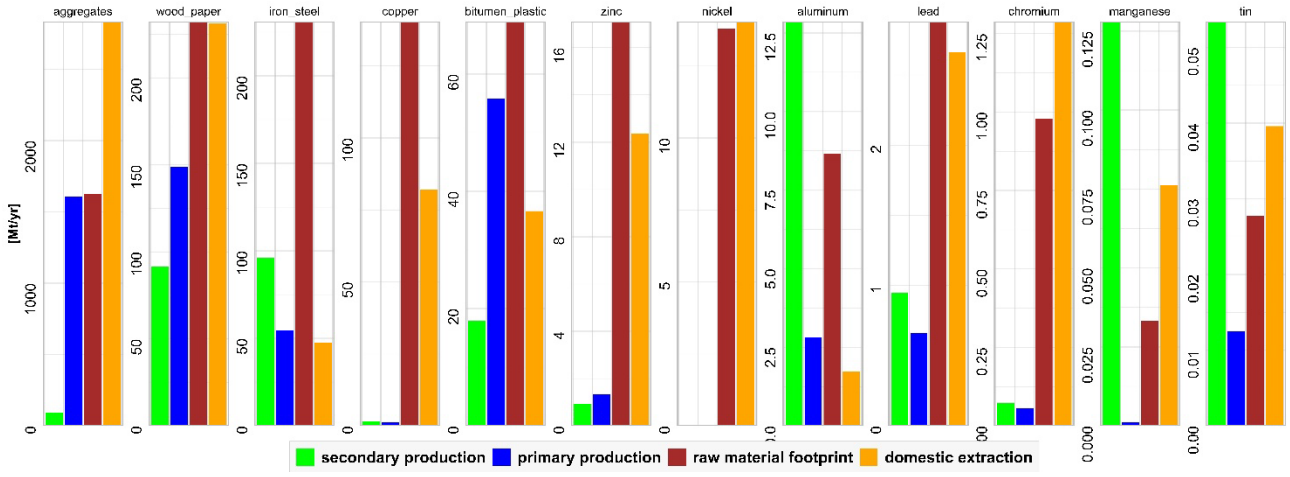


Figure 24: MFA indicators for EU27+3 material's production in 2022. Note the different scales on the y-axis per material, sorted descending from left to right according to total raw material footprint. The footprint quantifies the upstream raw material extraction (primary production + losses i.e. processing wastes) that is embodied in the primary production of the EU27+3 (e.g., steel making in EU27+3). All numbers are in Mt/year.

For stock-building materials such as metals, biomass and fossil-fuel based materials, we observe a good fit between IRP DE accounts, MISO2 production and international trade data and informed assumptions on alloying metals, ore grades and related process yields. The differences between MF and PMP across stock-building materials shown in Figure 24 are indicative of variations in yields and transfer coefficients (such as ore grades for metallic minerals), which are distinct for each of the material processing chains. For example, MF of aggregates is only marginally greater than PMP, which is due to the relatively high quarrying yield of 95% (compare (Aramendia et al. 2023) for this assumption). The MF of bitumen_plastic is ca. 20% larger than PMP, which is attributable to the processing yields in the petrochemical industry. Conversely, in the case of metals like nickel which has a global average ore grade of 3%, MF is with a factor 112 larger than PMP.

The IO-analysis showed that iron_steel MF (ca. 260 Mt/year) is about five times the volume of DE (ca. 50 Mt/year), which indicates a strong import dependency of iron_steel PMP in the EU27+3 (see details on import dependency further down below). Iron_steel accounts with ca 200 Mt/year for the largest RME imports of all materials assessed, which primarily stem from America (Brazil) and Asia/Pacific, i.e., Australia (See figure in Annex 9.5). For wood_paper, which has a slightly larger MF than iron_steel, MF and DE are quite balanced in total, both around 250 Mt/year. Consequently, imports and exports in the MF of wood_paper (around 50 Mt/year) are also very similar. Quite surprisingly, for some material processing chains like manganese, aluminum and tin, we find that

SMP exceeds MF, which indicates high circular material use rates for those materials, even when upstream raw material inputs are taken into account.

6.5.2 Assessing the (miss-)match between raw data on production, trade and extraction

In general, a key take-away message from Figure 24 is that for many materials processing chains, the physical IO model revealed reasonable results, which suggests a good agreement between relevant raw data sources used for linking material extraction with primary production. However, data integration for the material processing chains of aggregates, which depicts flows of sand and gravel for primary production of concrete, asphalt and base layers, turned out to be problematic. A considerable miss-match between data sources surfaced, which suggests further research is particularly relevant for minerals processing chains. Regarding concrete, please note that cement is not represented in the material processing chains, i.e. physical IO tables for aggregates, but only the sand and gravel used for the concrete.

The DE shown in Figure 24 depicts the extraction of raw materials within the EU27+3, which are exported, used domestically (addition to stocks), or directly discarded back to the environment (e.g. mining wastes). Our analysis revealed an MF for aggregates at approximately 50% of DE, which would indicate that the EU27+3 appears to be a net exporter of sand and gravel (see also the figure export/import by materials in Annex 9.5). However, it is widely acknowledged that construction materials such as sand and gravel are not traded internationally over larger distances in large quantities due to their relatively low prices and limited economic value, as well as their ubiquitary and relatively high abundance in the natural environment. DE of sand and gravel, as reported by the IRP database, and the PMP of aggregates, as estimated by MISO, demonstrate a strong correlation on a global scale (approximately 32 Gt/year in 2022). However, a comparison at the country level reveals substantial discrepancies between the two data sources, which are presumably attributable to the divergent approaches employed for estimating their extraction and demand (e.g. bottom-up vs top-down estimation, utilisation of production statistics and various material multipliers, as well as assumptions concerning secondary material flows and downcycling). The RAS balancing applied in the compilation of the physical IO models uses IRP extraction and MISO production as constraining values for the mass balancing. All “discrepancies” at the country level between DE and PMP are subsequently balanced through the manipulation of international trade flows. BACI trade data is only used for setting up the initial estimate of the physical IO model.

The estimated net-export for aggregates from the EU27+3 must be interpreted in light of the observed discrepancy between the different data sources that were used in the compilation of the physical IO model, as well as the modelling assumption i.e. data selection to set balancing constraints. An improved data reconciliation approach might also make use of BACI trade data as a constraining value instead of only the IRP extraction data. Such an approach could be deemed more useful, given the relatively high uncertainty associated with sand and gravel extraction ((Watari et al. 2025; Zhuang et al. 2025). In an ideal situation, the implementation of a more sophisticated RAS balancing algorithm such as Konfliktfreies-RAS (Lenzen, Gallego, and Wood 2009; Streeck et al. 2025) would be advantageous. Konfliktfreies-RAS facilitates the incorporation of uncertainty estimates for the different data sets, which can be used to integrate extraction and trade data in a more sophisticated manner, which better reflects the quality of the data.

6.5.3 Identifying import dependencies of material production in EU27+3 regions

Although we have questioned the MF and DE estimates for aggregates above, its import shares for the EU27+3 are with 10% in a realistic range which is to be expected (see Figure 25). With approx. 95-98%, material processing chains of iron_steel and aluminum are characterized by substantial import dependencies for upstream raw material extraction but also extraction-related CO2 and energy use. Bitumen_plastic, which accounts for the third largest PMP in EU27+3 regions (compare with Figure 24), is also characterized by a strong import-dependency (for oil and gas) of around 80%. In contrast, footprints of chromium, manganese, and tin production are almost exclusively domestic. Primary manganese and tin are produced in very small volumes in only a handful of EU27+3 countries. We find that these countries source their raw materials from within EU27+3. Further details on the regional source of imports (predominantly from the American continent and countries like Brazil and Chile) and regional destination of exports (predominantly Asia and China) across different material processing chains are contained in Annex 9.5.

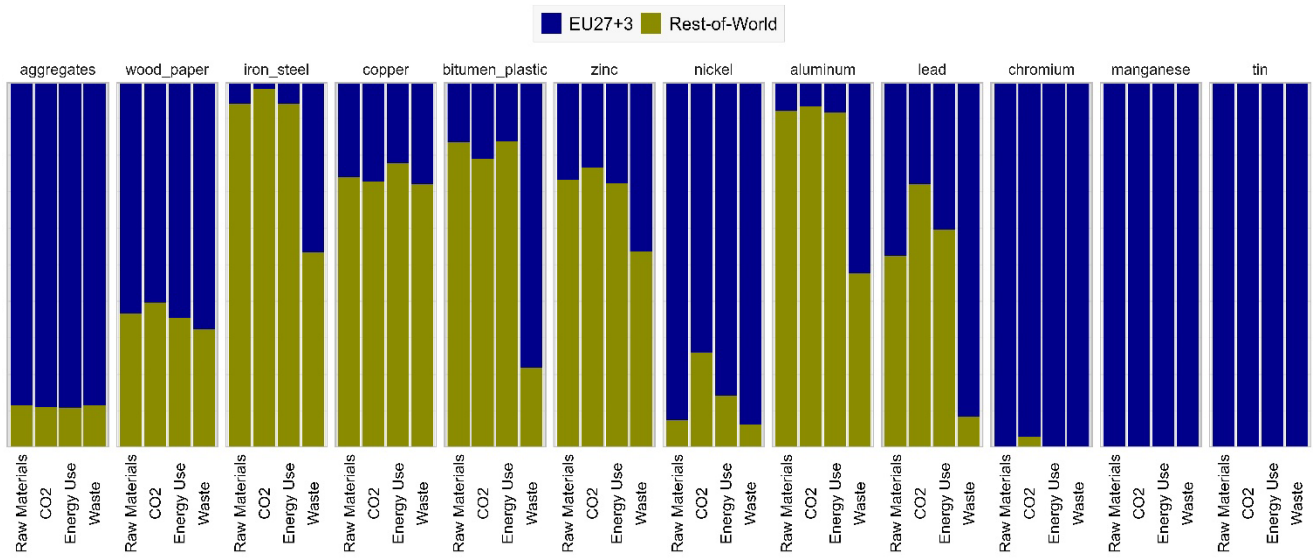


Figure 25: Source regions of the footprints of primary material's production in EU27+3 regions. Please note, that the footprint estimates shown here only refer to upstream raw material extraction, extraction-related CO2 emissions and energy use as well as wastes from primary raw materials. Please note that wastes refer to the unwanted materials that are contained in the extracted raw materials that are not destined for primary material production (e.g., mining wastes). The blue bars depict the fraction of EU27+3 footprint that is sourced domestically and the yellow bars the fraction imported from Rest-of-the-World.

A noteworthy highlight of our trade analysis pertains to the regional distribution of waste footprints in comparison to MF. As demonstrated in Figure 25, for materials such as aluminum, lead, zinc, iron_steel or bitumen_plastic, the domestic fraction in waste footprints (i.e., waste flows occurring within EU27+3 regions) is generally larger than the respective domestic fraction in MF. For example, while 95% of iron_steel MF is located outside EU27+3, 50% of the waste occurs domestically. In the context of metals, this can be attributed to ore grades of traded products and the necessity for subsequent processing and concentration (for instance, from 15% for nickel to its pure form), which consequently gives rise to domestic waste flows resulting from imported raw materials and international supply chains. For bitumen_plastic, where no such thing as “ore grades” exists, the observed pattern is very likely due to the material processing yields in the petrochemical industry (65-85%; which is in mass terms only moderately efficient), where imports are eventually refined domestically. The potential of mass-balanced physical IO analysis to reveal such patterns across global material supply chains can be seen as a considerable advantage over other methods like purely monetary IO or non-IO-based MFAs, which are worth noting here.

6.5.4 *Comparing CO2, energy and raw material footprints of material production in EU27+3*

As shown in Figure 26, while aggregates have the largest MF of all materials, their extraction-related energy and CO2 footprints are only second to that of bitumen_plastic. In comparison to the average production-based energy intensity of all the assessed stock-building materials (mean across all materials), mining and quarrying of sand and gravel has a comparatively small energy intensity per ton of raw material (25 MJ/t vs. 80 MJ/t). However, given the magnitude of these bulk flows (MF with 1600 Mt/year) in the material production of the EU27+3, the associated extraction-related energy footprint (ca. 75 PJ/year) and CO2 footprint (5.6 Mt/year) becomes large.

Prime reasons why bitumen_plastic has the largest CO2/energy footprint of all the stock-building materials assessed are as follows. Firstly, the production-based energy intensity of oil and gas extraction is with 1262 MJ/t approximately 16 times higher than the mean intensity across all stock-building material, and around 50 times higher than the intensity of sand and gravel quarrying. Second, due to reasons of data availability, the present physical IO analysis excludes large mineral supply chains, such as those for brick and glass production (see method section). This further increases the relative importance of bitumen_plastic when comparing the CO_2 and energy footprints of material production across different material groups.

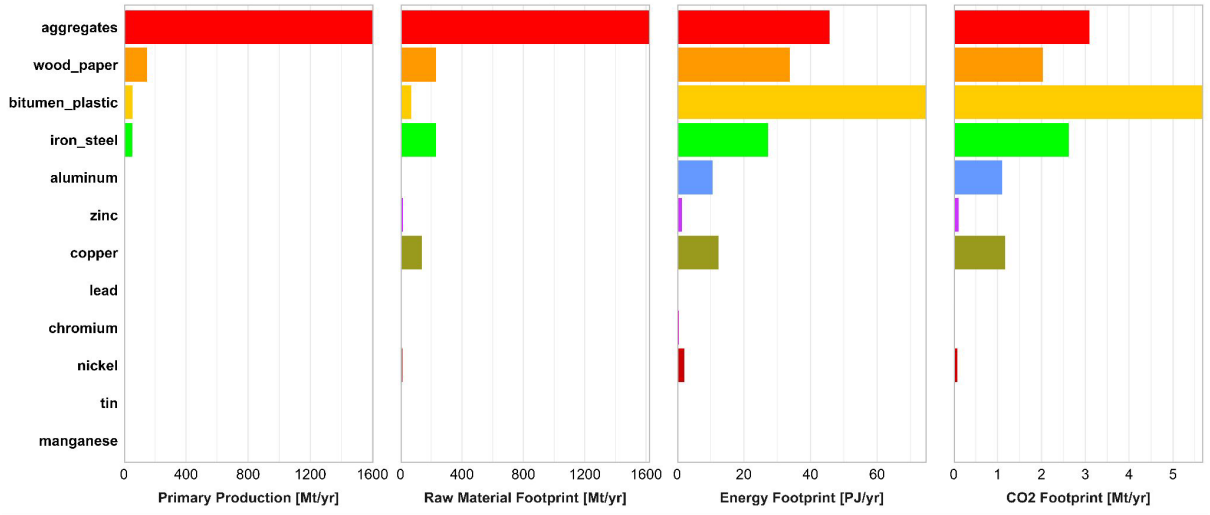


Figure 26: Primary production on the left and the different mining-related footprints of the EU27+3 by material processing chains. Year 2022. Materials are sorted from top to bottom according to primary production in the EU27-3. All footprints shown here quantify the upstream resource use embodied in the primary production within EU27+3 regions.

Regarding the material processing chain of bitumen_plastic, it is important to emphasize that non-energy hydrocarbons intended for the production of primary bitumen and plastic production are generally considered to be by-products of the fuel production process in the petrochemical industry. In reality, of course, oil and gas are not extracted solely for plastics and bitumen. However, in the physical IO footprint analysis for primary bitumen and plastic, the upstream extraction of oil and gas, as well as the associated extraction-related energy use and greenhouse gas (GHG) emissions, are estimated via mass balancing processes and international markets. Upstream resource use is allocated proportionally to the mass flow of these products, i.e. bitumen and plastic. In general, approx. 3–10% of fossil fuel inputs to refineries are attributable to bitumen and plastic flows, which is also reflected in the results of the IO analysis presented here.

7. Discussion

This deliverable reports on progress made towards stock-flow consistent and fully mass-balanced assessments of economy-wide circularity for materials, energy, and greenhouse gas (GHG) emissions in the EU27+3 countries. This includes developing novel indicators and advancing the empirical basis for the 'circular material use rate' currently used by the European Union as headline CE indicator. Previous work in this area focused solely on accounting for flows of material, energy, waste and GHG emissions separately within a year, missing out on the crucial role of socio-economic material stocks (Streeck et al. 2025) and the interrelations between materials and energy. The findings presented herein integrate official statistics on raw material extraction, energy use, waste generation and GHG emissions, using the dynamic stock-flow model MISO2 to consistently quantify material cycles and stocks. Its extension, MISO2+, explicitly quantifies the direct scope 1+2 energy use during those processes, as well as the associated energy-related GHG emissions. This approach enables a mass-balanced, stock-flow consistent analysis of the nexus between materials, energy, waste and GHG emissions.

The aims of this work are to offer novel insights into the status, potentials and limits of the circular economy (CE) for climate change mitigation at the national to European level. The modelling primarily monitors empirically observable progress towards a more sustainable circular economy. The economy-wide baseline estimates of realized material cycles and stocks also serve as benchmark for sector-specific work in CircEUlar (see Deliverable 2.3 and (Baumgart et al. under review)) as well as for scenario modelling in WP6 using the newly developed MESSAGEix-materials model (Ünlü et al. 2024). Additionally, scenario modelling using the MISO2+ model is being developed, which aims to explore the biophysically feasible option space for a sustainable circular economy in the European Union, considering the empirical evidence from WP5 and the scenario narratives developed in WP6.

7.1. Empirical insights

Herein, we advance CE monitoring by introducing a set of four macro-level headline indicators on (1) the scale of the biophysical economy, as well as on how (2-4) narrow, slow, and closed material cycles are. These indicators reveal that the EU27 has slightly narrowing material cycles (PM/year) since 2007 — although per capita usage is still high compared to the global average (section 6.2). We also find small improvements in slowing and closing of material cycles from 1990 to 2022. The CE

indicators (narrow, slow, close) introduced in the study offer valuable insights into material cycle dynamics but reveal a paradox: slowing material cycles does not necessarily lead to reduced overall material use. This highlights the need for complementary strategies which stabilize material stocks.

These material stocks grew continuously since the 1950s, summing to 175 Gt or 330 t/cap in the EU27+3 in 2022 (section 6.3; 154 Gt for EU states only). The corresponding stock-building material flows to build these stocks account for around 55% of overall material use (PM/year) in 2022 (section 6.1). Their extraction, processing and manufacturing are responsible for 78% of industrial energy use and 73% of energy-related GHG emissions in the EU27+3 in 2020 (section 6.4) — which declined by 37% for energy use and 53% for GHG emissions since 1990 (but in 2022 still made up 36% and 33% of overall energy use and GHG emissions, respectively). We also confirm the strong import dependency for key materials like iron and steel, with 95% of their material footprint (MF) located outside the EU27+3, while 50% of the waste footprint occurs domestically (section 6.5). This discrepancy underscores the role of international supply chains in shaping domestic waste flows and the need for improved circularity strategies.

The study also identifies significant limitations in existing data sources, such as Eurostat waste statistics as well as the official data on the 'circular material use (CMU)' rate (section 6.3.2). For instance, waste generation rates across the EU countries seems sometimes surprisingly low compared to modelled waste flows; also, waste reused within industries is frequently unreported, leading to gaps in the representation of material inflows and outflows. Furthermore, official data on the CMU as downloaded does not fully match officially reported values, indicating challenges in the underlying data. In contrast, the MISO2 model provides a more holistic perspective by explicitly linking material flows across the socioeconomic system. This approach reveals substantial gaps in reported data and emphasizes the importance of integrating waste statistics with material flow accounts.

7.2. Limitations and next steps

The key challenges tackled in this work lie in the detailed but also system-level consistent linking of energy use and GHG emissions with economy-wide material and waste flows, as well as material stocks. For instance, the estimates of energy use and GHG emissions in this study were derived through a combination of top-down and bottom-up approaches. In the top-down perspective, we accounted for the overall energy requirements and emissions associated with all processes and

materials, drawing on official statistics such as from IEA. The bottom-up perspective then distributed these totals across individual MISO2 processes, materials, and products, using intensity factors sourced from LCA studies. A challenge arises because these LCA intensity factors are typically defined for very specific processes or products (e.g., “production of refrigerant R134a” or “manufacture of a black-and-white laser printer”), whereas the MISO2+ model is a systemic, economy-wide MFA framework that represents much broader categories of processes. To mitigate this mismatch, we compiled sets of comparable processes from the LCA literature and applied the mean of their intensities in our calculations. While this provides a workable approximation, it inevitably smooths over the variability between individual processes. Therefore, a more systematic assessment of the uncertainty and range of possible values for energy use and GHG emissions across MISO processes, materials, and products is required. We identify this as a crucial next step to improve the robustness and interpretability of the results.

The second crucial challenge addressed herein pertains to the mass-balanced and stock-flow consistent integration of the available data on raw material extraction, trade, industrial production, stock dynamics, as well as waste generation and recycling. The lack of harmonized and comprehensive waste data limits the ability to fully quantify domestic processed outputs and their environmental impacts. Addressing this requires improved data collection methods and the integration of waste statistics with material flow accounts to provide a more holistic perspective. Currently, waste flows modelled using MISO2 agree relatively well with total waste generation as reported by Eurostat. However, substantial divergences appear when looking into specific countries and/or materials. Clearly, model parameters could be tuned to match modelled results to official statistics. However, widespread concern among waste management researchers and the literature about waste estimates rather suggest that the urgent need to improve the robustness and harmonized reporting in official waste and recycling statistics.

In conclusion, the next steps involve refining the MISO2+ model assumptions to address data uncertainties, improving the harmonization of material and waste flow data, and exploring the interplay between circularity and decarbonization strategies. These efforts will be essential for advancing a systems-oriented approach to circularity and supporting the transition to a low-carbon, circular economy in the EU27+3. In addition, the commenced efforts to assess CE not only via indicators for the EU territory but including upstream effects via footprint indicators seems like a promising avenue to evaluate CE more holistically.

8. Conclusions

We find that the EU27 shows slightly narrowing total material use (PM/year) since 2007 and small improvements in slowing and closing material cycles over the period from 2000 to 2022. We also find that material stocks continue to grow across all EU states, which hinders substantial progress in further narrowing material cycles. As long as stocks are growing, more virgin materials are going to be required than can be supplied via more closed material cycles. Due to persisting limitations of data availability and linkage, further steps are required to achieve fully consistent integration of data on extraction, trade, industrial production, stock dynamics, waste, recycling, energy use and emissions in the future.

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9. Annex – supplementary information and data sources

9.1. Data Update and Triangulation of MISO2 material flows & stocks

9.1.1 Update of the data on production of engineered materials to 2022

Table 7 gives an overview of the data sources used for the update of the MISO2 input data for crude material production (P3) from version 1.0 to until the year 2022.

Table 7: Summary table on the primary data used for the 2022 material production data update (MISO2 input data v.1.1) versus the data sources used in the first i.e. original version of the production data till 2016 (MISO2 input data version 1.0.1). For materials where no data source is listed, we extrapolated the 2016 data to 2022 using the most suitable proxy. The acronyms are as follows. BGS = British Geological Survey, USGS = United States Geological Survey, IEA = International Energy Agency, FAOSTAT = Food and Agriculture Organization Statistics, UNICPS = UN industrial commodity production statistics, WBMS = World Bureau for Metal Statistics.

Material	**Original data source (MISO2 v1.0)**	**Update data source (MISO2 v1.1)**
Cement	Cembureau	USGS
Bitumen	IEA, UNICPS	IEA, UN energy statistics
Plastics	IEA, additional sources	IEA, UN energy statistics
Bricks	UNICPS, additional sources	Prodcom/Eurostat for EU regions
Paper	FAOSTAT	FAOSTAT
Wood	FAOSTAT	FAOSTAT
Iron & steel	WorldSteel Association	WorldSteel Association
Aluminium	WBMS, BGS	BGS
Copper	WBMS	BGS
Lead	BGS, USGS	BGS
Zinc	BGS	BGS
Chromium	WBMS	BGS
Nickel	BGS	BGS
Manganese	BGS	BGS
Tin	BGS	BGS
Container glass	UNICPS, glassglobal	Prodcom/Eurostat for EU regions
Flat glass	UNICPS, glassglobal	Prodcom/Eurostat for EU regions

For a summary of the construction of the MISO2 input data version 1.0 covering the years 1900 to 2016, see (Plank et al. 2022b, 2022a; Wiedenhofer, Streeck, Wieland, Grammer, Baumgart, Plank, et al. 2024). The entire production data update to 2022 is semi-automated through R script, which can be seen as a major step toward better reproducibility as opposed to the spreadsheet-based approach taken in MISO2 v1.

Unfortunately, several data sources which were used to parametrize the MISO2 input dataset v1.0 were discontinued and could therefore not be used to update the time series to 2022. This includes, for example, Cembureau data on cement production or the UN's industry commodity production statistics (UNICPS) for bitumen and bricks. Where no adequate primary data source was found (i.e., container glass, flat glass and bricks production for non-EU countries), we extrapolated the 2016 time series to 2022 using suitable proxies such as per capita GDP or population numbers (see text below). If the MISO2 input data v1.1update does not contain production data for a specific material in a specific region but MISO2 input data v1.0 does, we extrapolated 2016 data to 2022.

Because of partially unavailable data sources and because the original MISO2 input data v1.0 contains extrapolated production data for some of the last years of its times series, the basic approach for the production data update to 2022 (MISO2 input data v1.1) was to replace all data points from/including 2012 onwards (see exceptions mentioned below). Uncertainty scores for all data sources (Plank et al. 2022b, 2022a; Wiedenhofer, Streeck, Wieland, Grammer, Baumgart, Plank, et al. 2024) were extended and adjusted accordingly. In the following we summarize the data update for specific key materials for which additional adjustments were made:

- **Aluminum**: BGS data reports primary aluminum production, which were used without any further transformations. Production data for the United Arab Emirates (UAE), which is the fourth largest aluminum producer in the world, was missing in the MISO2 input data v1.0 data set. According to BGS, aluminum production in the UAE started in 1980. Other country data in the MISO2 v1.1 update started in 2012.
- **Bitumen** and **plastics**: The update of (fossil fuels-derived) bitumen and plastics production both make use of the IEA extended energy balances and UN energy statistics, which report the energy-content of intermediate flows that allow approximating primary production of these materials. Due to unit errors in the MISO2 input data v1.0 with missing conversions from tons of oil equivalent to metric tons, and the general lack of a reproducible modelling approach, all numbers

starting from 1990 were replaced. 1990 was chosen due to pragmatic reasons as this is the first year where Russia is reported as an independent country. We consider IEA data to be superior and only make use of UN energy statistics where IEA does not report data. Comparison of results derived from IEA and UN statistics revealed very similar estimates. Plastics production is approximated by summing up the feedstock of the petrochemical industry, which is reported as non-energy use in energy statistics, and applying an average yield factor of 86%, which was also used in the MISO2 input data v1.0 by Plank and colleagues see (Plank et al. 2022b, 2022a) Bitumen production is reported in the energy statistics through "supply of transformation processes". UN energy statistics report plastic and bitumen flows in mass units (metric tons) whereas IEA reports flow only in energy units (tons oil equivalent). We applied region-specific conversion factors (e.g. 0.93 tons of oil equivalent per metric ton of bitumen) sourced from the IEA to convert data from energy into mass flows.

- **Cement**: The original MISO2 input data v1.0 till 2016 from Cembureau is considered to be superior to data derived from USGS, which is why we added new data only from 2017 onwards. Our comparison of v1.0 and v1.1 production data for overlapping years showed that both data are highly consistent though. The USGS numbers used for the MISO data set refer to USGS's account of hydraulic cement.
- **Chromium**: The original data source for the MISO2 input data v1.0 WBMS, is considered to be superior to the new MISO2 input data v1.1 data source BGS, because it reported metal content as opposed to gross ores. We estimated country-wise ore grades using the overlapping years (2014-2016) and transformed the new BGS data from gross ore into metal content. The update of the chromium production data starts in 2017 and applied the estimated ore grades to relate to metal content.
- **Lead**: We identified an error in the data processing of the MISO2 input data v1.0 lead production data. Tracing back the error, we found that the original production data is only reliable till 1995. The start year of the lead data update in v1.1 until 2022 is therefore 1995.
- **Manganese**: Due to a data processing error in the MISO2 input data version 1.0 for South Africa, the largest manganese producer in the world, we corrected and replaced the entire South Africa country data in the update to v1.1. The updated South Africa country data starts in 1971, and all other regions in 2012.

- **Wood** and **paper**: FAOSTAT has updated the production accounts for a few regions that were used in the modelling of wood and paper production. We observed only small differences between versions 1.0 and v1.1 for wood and paper production data. However, replacing a larger fraction of the wood and paper production time series seemed necessary. Due to pragmatic reasons, such as already available disaggregations of regions such as the Former Soviet Union and others, we decided to update numbers from 1992 onwards.

9.1.2 Update of trade data to 2022

In the MISO2 input data v1.0, the trade database UN COMTRADE was used to estimate material trade flows at different processing stages due to its longer historical time series, which dates to the 1960s. To update the time series of trade data for stock-building materials up to 2022, the product-level trade database BACI was used as the primary data source. BACI, (CEPII 2025)provided by CEPII, is based on the UN COMTRADE database of the United Nations Statistical Division but applies further processing.

The key advantage of using the BACI database over the original COMTRADE database lies in its data consolidation and harmonization efforts, as described below. Ideally, international trade is reported by both exporting and importing countries in monetary terms as well as in physical units, resulting in so-called "mirror flows." Depending on whether the exporting or importing country reports the trade, the value of the traded goods may include or exclude transport costs. In practice, however, not all trade is reported by both the exporter and importer, and physical units often depend on the type of product traded (e.g., cubic meters for wood or square meters for bulk freight like grain). In some cases, physical units are missing altogether. The BACI database reconciles discrepancies in reported export and import data for both monetary values and physical units using statistical methods. It also converts available physical non-mass units (e.g., volume) into tons. As a result BACI offers a comprehensive database covering more than 200 countries and 5,000 products, available in different HS classifications, which can be used to study material flows in international trade. For detailed documentation, see (Gaulier and Zignago 2010).

To map the BACI trade data at the product level (with over 5,000 product codes) into the 18 material categories covered in the MISO2 input data, as well as to assign product codes to processing stages (cf. MISO2 system definition, Figure 3), a concordance between the BACI commodity codes (in this case, the HS0 classification system) and the MISO2 material types and processing stages is required.

As a starting point, we used information from the Eurostat ew-MEFA framework, which provides a mapping of CN codes (a more detailed European system based on the international HS system) to ew-MEFA material types and to three processing stages: raw material, semi-finished product, and final product. In this framework commodities containing more than one ew-MEFA material type are assigned to the material type with the highest mass share.

Using the Eurostat ew-MEFA material types, we determined whether an BACI trade code (HS0) is stock-building or not. However, for approximately 3,800 codes, this decision was not possible based on the information provided by the ew-MEFA material types. These codes either belonged to aggregate categories such as "Other Products" or "Products Mainly from Biomass," or their Eurostat category was not clearly indicative of whether the commodity is stock-building or not. For these cases, we manually classified the commodities according to their labels in HS0, CN and SITC1 commodity classification. We considered all products with uses extending one year as stock-building. For petrochemicals (approximately 400 codes), the primary uses of each product were researched (e.g., using Wikipedia), and the product code was classified as stock-building if it was primarily used as plastic feedstock

In addition, we modified the original mapping from Eurostat in several ways:

First, regarding processing stages, the MISO2 model includes an additional production stage—raw products—before the semi-finished product stage. To account for this, product codes within Eurostat's "semi-finished product“ group as well as codes that Eurostat does not assign a processing stage to were manually reassigned to either raw- or semi-finished products. Since it is not always clear which processing stage a product should belong to, the following classification rules were established: ingots are classified as raw products; sheets of metal, pipes, wires, tubes, paper, and fabrics are classified as semi-finished products; while clothing, washers, nuts, and bolts are classified as final products. All commodities described as “articles” or “products” in the short description of the HS0 classification were classified as final products. This manual reassignment process involved approximately 1,000 codes.

Second, regarding material types, based on the updated production stages, the material category specified by the Eurostat ew-MEFA classification was adapted for all commodities with a processing stage lower than "final product." This approach assumes that, due to the simpler composition of

intermediate products, the misclassified material mass is small. In the Eurostat framework, there are other aggregate categories such as "Other Products," "Products Mainly from Biomass," or "Products Mainly from Non-Metallic Minerals" for which correspondence to a specific material was unclear. We assigned the codes in these categories, around 3,800 in total, to the MISO2 material categories manually according to their labels in HS0, CN and SITC1 commodity classification

As a final step, material intensity —information on the share of material types contained in the product— was required for all commodities classified as final products. Here, we built on work done for the MISO2 input data v1.0.(Plank et al. 2022b, 2022a) which collected data on material intensities of (final) products for over 300 commodities in the SITC1 system. Using the concordance between the HS0 and SITC1 systems provided by the World Bank, these material intensities were assigned to the corresponding HS0 codes. For final products still missing a material intensity, the closest match within the SITC1 system was selected manually and checked for plausibility.
Using this concordance, BACI trade data for trade within, out of, or into the MISO2 region was mapped onto the MISO2 material categories and processing stages and is subsequently used as input trade data for the MISO2 model from 1995 to 2022. To align with the MISO2 geographical country classification, the BACI trade data was mapped to the MISO2 country classification. From 1995 to 2022, several countries separated: Serbia & Montenegro and South Sudan & Sudan, in addition to Belgium & Luxembourg, which used to report trade in a joint account. As MISO2 reports its results for countries that currently exist, the historical reports in the joint account were divided according to the population of the respective country parts and attributed to the current countries.

9.1.3 Update of recycling and downcycling flows and rates to 2022

To remain as close to real-world data as possible, absolute waste flows (metric tons per year) as reported in official statistics of Eurostat (Eurostat 2025) (2025) and the United States Geological Survey (USGS 2025b) were used as inputs to MISO2 v1.1 (Table 8). These data were largely available for all countries of the EU27 region and the last one to two decades. The representation of recycling in MISO2 v1.1 is therefore largely improved from the predecessor version where recycling rates for individual countries and years from various literature sources were used - this data being only available for certain years which required interpolation and use of average factors.
However, Eurostat reports recycling flows in a variety of categories with their level of aggregation complicating their integration with ew-MFA and MISO2 due to differing definitions (see methods

section for more information on matching Eurostat with MISO2 waste categories). For example, while construction and demolition (C&D) waste flows are reported as an aggregate category by Eurostat, MISO2 requires more explicit material-centered categories such as concrete, bricks, flat glass, and aggregates.

As a result, all flows reported by Eurostat whose categories directly correspond to MISO2 waste flow categories were used as absolute EOL recycling flows, meaning that we assumed the reported flows corresponding to old scrap arising from discarded material stocks. This is the case for iron and steel, wood, plastic, and container glass (it was assumed that this corresponds to the container glass category used in MISO2). For paper, we assumed that Eurostat recycling flows correspond to total recycling, affecting both old and new scrap, with the latter arising from various processing stages during production.

Table 8: Overview of new data sources and types of inputs for MISO2 1.1 material categories.

Material	**Data source (MISO2 v1.1)**	**Input type**
Container glass	Eurostat	EOL Absolute Recycling
Paper	Eurostat	Total Absolute Recycling
Wood	Eurostat	EOL Absolute Recycling
Plastic	Eurostat	EOL Absolute Recycling
Iron & steel	Eurostat	EOL Absolute Recycling
Aluminum	USGS	EOL Absolute Recycling
Copper	USGS	EOL Absolute Recycling
Lead	USGS	EOL Absolute Recycling
Asphalt	EAPA	EOL Recycling Rate / Downcycling
All other materials	No change	Rates used as in MISO2 v1.0

Data from sources other than Eurostat was used for non-ferrous metals and asphalt. For non-ferrous metals Eurostat reports waste flows as aggregate category. For more resolution, USGS data was used to provide absolute recycling flow information on three major non-ferrous metals, namely aluminum, copper and lead. For this purpose, the reported secondary production quantity was used as EOL absolute recycling inputs to the model, as it was assumed that recycling of new scrap occurs within production, and is consequently likely to not be reported. For all other non-ferrous metals such as

zinc, chromium, tin, manganese, and nickel, neither Eurostat nor USGS reported absolute waste flows. Therefore, the recycling rates for the last year available from MISO2 v1.0 were used.

For asphalt, the availability of recycling data is very precarious. While the EAPA (2025) reports recycling flows and rates, these are substantially lower compared to our MISO2 estimate of end-of-life asphalt flows from road deconstruction. Although no data are available to explain this discrepancy, and further research into this is required, it seems likely that the EAPA (2025) reported waste flows only represent a partial share of the actual end-of-life outflows. To stay consistent with MISO2 estimates for asphalt end-of-life outflows, which are modelled from asphalt flows into road construction and average road lifetimes, we decided to use recycling rates instead of absolute flows. Recycling rates are based on the share of total recycled asphalt (hot- and cold-mix) in total generation of waste asphalt, as reported by EAPA (EAPA 2025) (2025).

9.2. Assessment of direct energy use and GHG emissions (from fossil-fuel combustion) of stock-building material flows

*Table 9: Description of energy consuming processes in MISO2+ by material (P1-P5) and by end-use (P7 and P9). * Indicates the application of aluminium recycling values for other metals due to missing factors*

	Extraction of raw materials (P1)	***Refining / smelting to raw products (P3)***	**Recycling / downcycling (P13)**	***Fabricating semi-finished products (P5)***	***Manufacturing final products (P7)***	***Construction (P9)***
Material / End-use (below) ***MISO flow (to the right)***	F_1_2_raw_material	F_3_4a_prod_primary_raw_prod_exog, F_3_4b_prod_primary_raw_prod_endog	F_13_20a_prod_recycle, F_13_20b_prod_downcycle	F_5_6_prod_semis	F_7_8_prod_finals	F_9_10_GAS
aggr_4asph	Extraction of sand and gravel for asphalt			Asphalt production		
aggr_4concr	Extraction of sand and gravel for concrete			Concrete production		
aggr_downcycl			1) Sorting 2) Recycling			
aggr_virgin	Extraction of sand and gravel for base layers		1) Sorting 2) Recycling			

aluminum	Extraction of Bauxite	1) Aluminium oxide production 2) Liquid aluminium production 3) Ingot aluminium production / Cast alloy slap production	1) Sorting 2) Treatment at remelter 3) Treatment at refiner	Bar extrusion / Sheet rolling		
asphalt						
bitumen	Approximation of oil and gas extraction which can be allocated to bitumen production					
bricks	Extraction of various kinds of clays and other brick-building materials	Brick production	1) Sorting 2) Recycling			
cement		1) Clinker production 2) Cement production				
chromium	Extraction of chromium ores	Chromium production	1) Sorting 2) Treatment at remelter 3) Treatment at refiner *	Portachrom (colouring), Chromium oxide production (flakes), e.g. coating		
concrete						
copper	Extraction of copper ores	1) Smelting of copper concentrate (anode) / copper production (cathode) 2) Electrorefining	1) Sorted 2) Remelting 3) Refining / Hydro- or pyrometallurgical processing	Sheet rolling / Wire drawing		
glass_cont	Extraction of industrial sand and gravel for glass production and associated	Packaging glass production	1) Sorting 2) Re-Production			

	raw materials					
glass_flat	Extraction of industrial sand and gravel for glass production and associated raw materials	Flat glass production				
iron_steel	Extraction of iron ore	1) Iron sinter/pellet production 2) Pig iron production 3) Steel production	1) Sorting and pressing scrap 2) Steel production	Casting / Rolling		
lead	Extraction of lead ores	primary lead production	1) Sorting 2) Remelting 3) Refining / Hydro- or pyrometallurgical processing	Battery production		
manganese	Extraction of manganese ores	Manganese production	1) Sorting 2) Treatment at remelter 3) Treatment at refiner * / Hydro- or pyrometallurgical processing	Manganese sulfate/dioxide (III) oxide production		
nickel	Extraction of nickel ores	Smelting, Refining	1) Sorting 2) Treatment at remelter 3) Treatment at refiner * / Hydro- or pyrometallurgical processing	Nickel sulfate/ processing nickel-rich materials		
paper	Timber harvest	1) Debarking 2) Pulp production	1) Sorting 2) Paper production recycled	Paper production		
plastic	Extracted gas and oil that can be allocated to plastic production	Primary plastic production	1) Sorting 2) Recycling	Plastic products production		

tin	Extraction of tin ores	Tin production	1) Sorting 2) Treatment at remelter 3) Treatment at refiner *			
wood	Timber harvest	Debarking		Sawnwood (Boards etc)		
zinc	Extraction of zinz ores	Zinc production / Zincmonosulfate production	1) Sorting 2) Treatment at remelter 3) Treatment at refiner * / Hydro- or pyrometallurgical processing	Zinc sulfide/oxide production		
Computers_and_precision_instruments					E.g. computer, disk drive, display, printer, …	
Electrical_equipment					Electric motor, electronics, transformer	
Machinery_and_equipment					Washing machine, refrigerator	
Motor_vehicles_trailers_and_semi-trailers					Passenger car production	
Other_transport_equipment					Aircraft, ferry, locomotove, train production	
Textiles					Bleaching, dyeing, finishing	
Food_packaging						
Furniture_and_other_manufactured_goods_nec					Wooden furniture, mattress production, timber	
Printed_matter_and_recorded_media					Printing	
Products_nec					Soap production	
Residential_buildings						Building

						construction
Non_residential_buildings						Building construction
Civil_engineering_except_roads						Railway track construction
Roads						Road construction and maintenance

Table 10: MISO processes, MISO flows, MISO materials or end-uses and allocated IEA flows.

MISO process	**MISO flow**	**MISO material/end-use**	**IEA flow**	**IEA flow name**	**IEA definition**
P3	F_3_4a_prod_primary_raw_prod_exog	aluminum	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P3	F_3_4a_prod_primary_raw_prod_exog	chromium	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P3	F_3_4a_prod_primary_raw_prod_exog	manganese	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P3	F_3_4a_prod_primary_raw_prod_exog	nickel	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P3	F_3_4a_prod_primary_raw_prod_exog	tin	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P3	F_3_4b_prod_primary_raw_prod_endog	copper	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P3	F_3_4b_prod_primary_raw_prod_endog	lead	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P3	F_3_4b_prod_primary_raw_prod_endog	zinc	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P3	F_3_4a_prod_primary_raw_prod_exog	bricks	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.

P3	F_3_4a_prod_primary_raw_prod_exog	glass_flat	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P3	F_3_4a_prod_primary_raw_prod_exog	cement	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P3	F_3_4b_prod_primary_raw_prod_endog	glass_cont	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P3	F_3_4b_prod_primary_raw_prod_endog	iron_steel	IRONSTL	Iron and steel	[ISIC Rev. 4 Group 241 and Class 2431]
P3	F_3_4b_prod_primary_raw_prod_endog	paper	PAPERPRO	Paper, pulp and printing	[ISIC Rev. 4 Divisions 17 and 18]
P3	F_3_4a_prod_primary_raw_prod_exog	plastic	CHEMICAL	Chemical and petrochemical	[ISIC Rev. 4 Divisions 20 and 21] Excluding petrochemical feedstocks.
P3	F_3_4a_prod_primary_raw_prod_exog	wood	WOODPRO	Wood and wood products	[ISIC Rev. 4 Division 16] Wood and wood products other than pulp and paper.
P5	F_5_6_prod_semis	aggr_4asph	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P5	F_5_6_prod_semis	aggr_4concr	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P5	F_5_6_prod_semis	aluminum	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P5	F_5_6_prod_semis	chromium	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P5	F_5_6_prod_semis	manganese	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P5	F_5_6_prod_semis	nickel	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P5	F_5_6_prod_semis	copper	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P5	F_5_6_prod_semis	lead	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P5	F_5_6_prod_semis	zinc	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P5	F_5_6_prod_semis	iron_steel	IRONSTL	Iron and steel	[ISIC Rev. 4 Group 241 and Class 2431]

P5	F_5_6_prod_semis	paper	PAPERPRO	Paper, pulp and printing	[ISIC Rev. 4 Divisions 17 and 18]
P5	F_5_6_prod_semis	plastic	INONSPEC	Industry not elsewhere specified	Including but not limited to: [ISIC Rev. 4 Divisions 22, 31 and 32] Any industry not included above.
P5	F_5_6_prod_semis	wood	WOODPRO	Wood and wood products	[ISIC Rev. 4 Division 16] Wood and wood products other than pulp and paper.
P7	F_7_8_prod_finals	Computers_and_precision_instruments	MACHINE	Machinery	[ISIC Rev. 4 Divisions 25 to 28] Fabricated metal products, machinery and equipment other than transport equipment.
P7	F_7_8_prod_finals	Electrical_equipment	MACHINE	Machinery	[ISIC Rev. 4 Divisions 25 to 28] Fabricated metal products, machinery and equipment other than transport equipment.
P7	F_7_8_prod_finals	Machinery_and_equipment	MACHINE	Machinery	[ISIC Rev. 4 Divisions 25 to 28] Fabricated metal products, machinery and equipment other than transport equipment.
P7	F_7_8_prod_finals	Motor_vehicles_trailers_and_semi-trailers	TRANSEQ	Transport equipment	[ISIC Rev. 4 Divisions 29 and 30]
P7	F_7_8_prod_finals	Other_transport_equipment	TRANSEQ	Transport equipment	[ISIC Rev. 4 Divisions 29 and 30]
P7	F_7_8_prod_finals	Textiles	TEXTILES	Textile and leather	[ISIC Rev. 4 Divisions 13 to 15]
P7	F_7_8_prod_finals	Food_packaging	INONSPEC	Industry not elsewhere specified	Including but not limited to: [ISIC Rev. 4 Divisions 22, 31 and 32] Any industry not included above.
P7	F_7_8_prod_finals	Furniture_and_other_manufactured_goods_nec	INONSPEC	Industry not elsewhere specified	Including but not limited to: [ISIC Rev. 4 Divisions 22, 31 and 32] Any industry not included above.
P7	F_7_8_prod_finals	Printed_matter_and_recorded_media	INONSPEC	Industry not elsewhere specified	Including but not limited to: [ISIC Rev. 4 Divisions 22, 31 and 32] Any industry not included above.
P7	F_7_8_prod_finals	Products_nec	INONSPEC	Industry not elsewhere specified	Including but not limited to: [ISIC Rev. 4 Divisions 22, 31 and 32] Any industry not included above.
P9	F_9_10_GAS_enduse	Residential_buildings	CONSTRUC	Construction	[ISIC Rev. 4 Divisions 41 to 43]
P9	F_9_10_GAS_enduse	Non_residential_buildings	CONSTRUC	Construction	[ISIC Rev. 4 Divisions 41 to 43]
P9	F_9_10_GAS_enduse	Civil_engineering_except_roads	CONSTRUC	Construction	[ISIC Rev. 4 Divisions 41 to 43]
P9	F_9_10_GAS_enduse	Roads	CONST	Construction	[ISIC Rev. 4 Divisions 41 to 43]

			RUC		
P13	F_20_4b_prod_downcycl	aggr_downcycl	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P13	F_20_4a_prod_recycle	aggr_virgin	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P13	F_20_4a_prod_recycle	aluminum	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P13	F_20_4a_prod_recycle	asphalt	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P13	F_20_4a_prod_recycle	bricks	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P13	F_20_4a_prod_recycle	chromium	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P13	F_20_4a_prod_recycle	concrete	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P13	F_20_4a_prod_recycle	copper	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P13	F_20_4a_prod_recycle	glass_cont	NONMET	Non-metallic minerals	[ISIC Rev. 4 Division 23] Such as glass, ceramic, cement, etc.
P13	F_20_4a_prod_recycle	iron_steel	IRONSTL	Iron and steel	[ISIC Rev. 4 Group 241 and Class 2431]
P13	F_20_4a_prod_recycle	lead	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P13	F_20_4a_prod_recycle	manganese	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P13	F_20_4a_prod_recycle	nickel	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.
P13	F_20_4a_prod_recycle	paper	PAPERPRO	Paper, pulp and printing	[ISIC Rev. 4 Divisions 17 and 18]
P13	F_20_4a_prod_recycle	plastic	CHEMICAL	Chemical and petrochemical	[ISIC Rev. 4 Divisions 20 and 21] Excluding petrochemical feedstocks.
P13	F_20_4a_prod_recycle	tin	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.

P13	F_20_4a_prod_recycle	wood	WOOD PRO	Wood and wood products	[ISIC Rev. 4 Division 16] Wood and wood products other than pulp and paper.
P13	F_20_4a_prod_recycle	zinc	NONFERR	Non-ferrous metals	[ISIC Rev. 4 Group 242 and Class 2432] Basic industries.

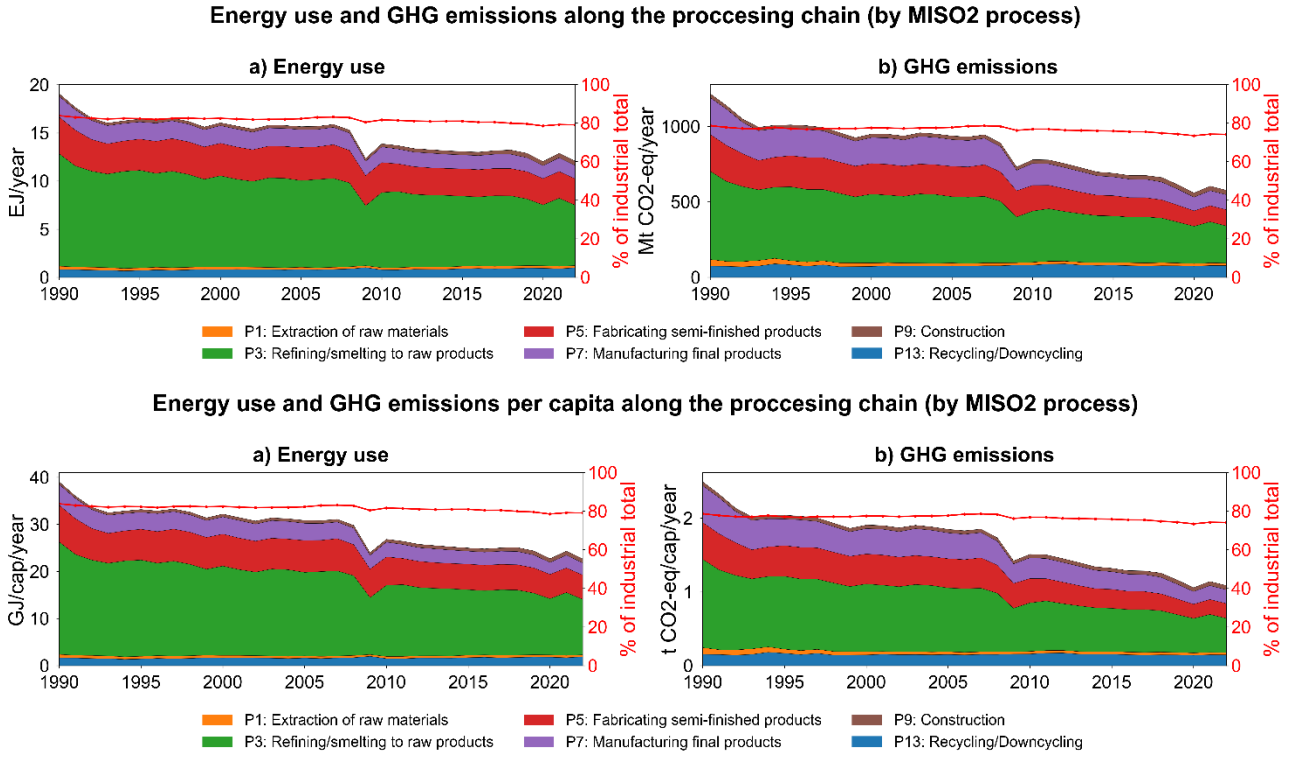


Figure 27: EU27+3 energy use and GHG emissions related to stock-building material flows at scale (top panels) and per capita (bottom panels).

9.3 Economy-wide circularity assessment

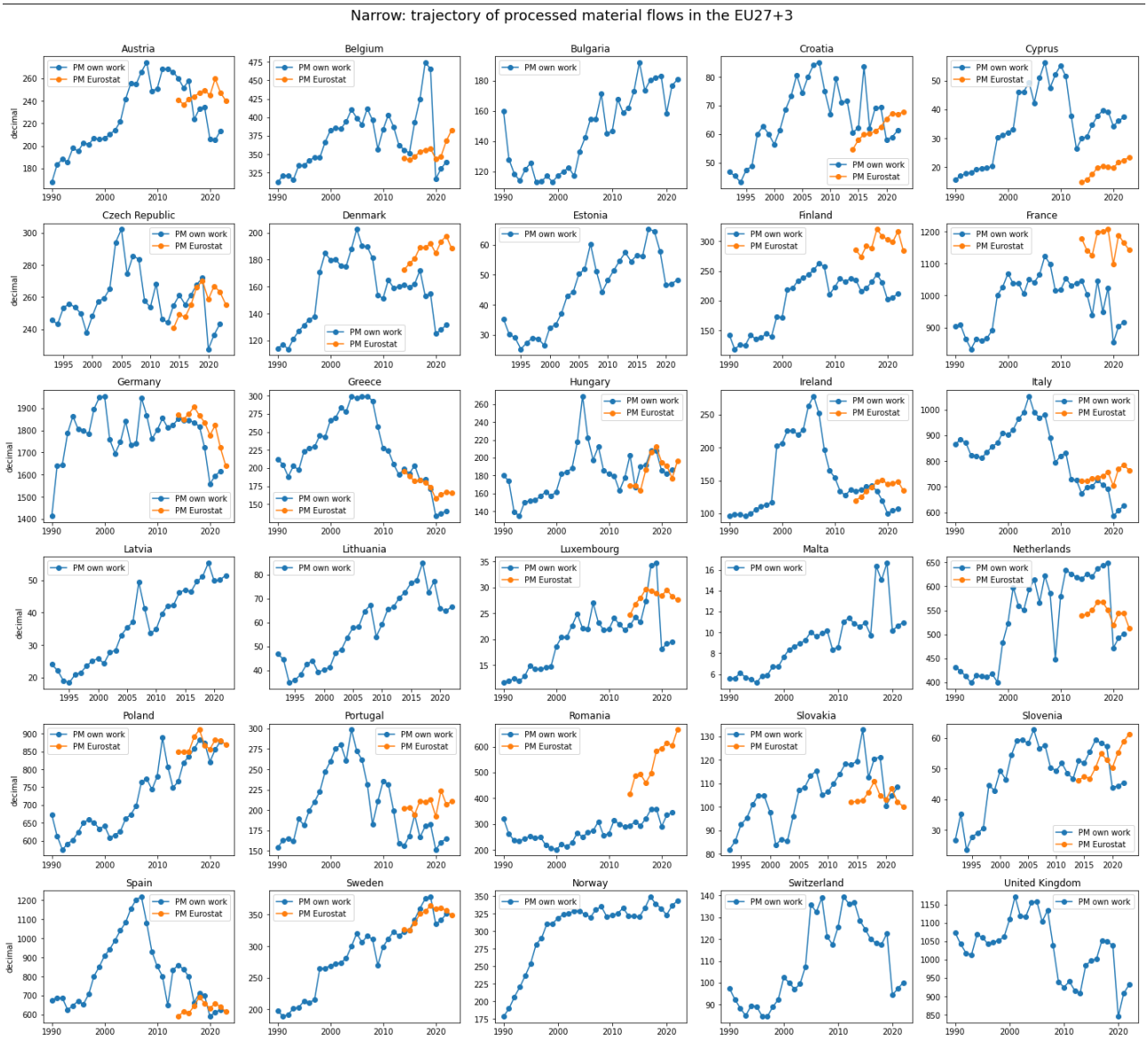


Figure 28:Temporal developments of processed materials (PM) in EU27+3 countries (see methods section 5.4 for indicator details).

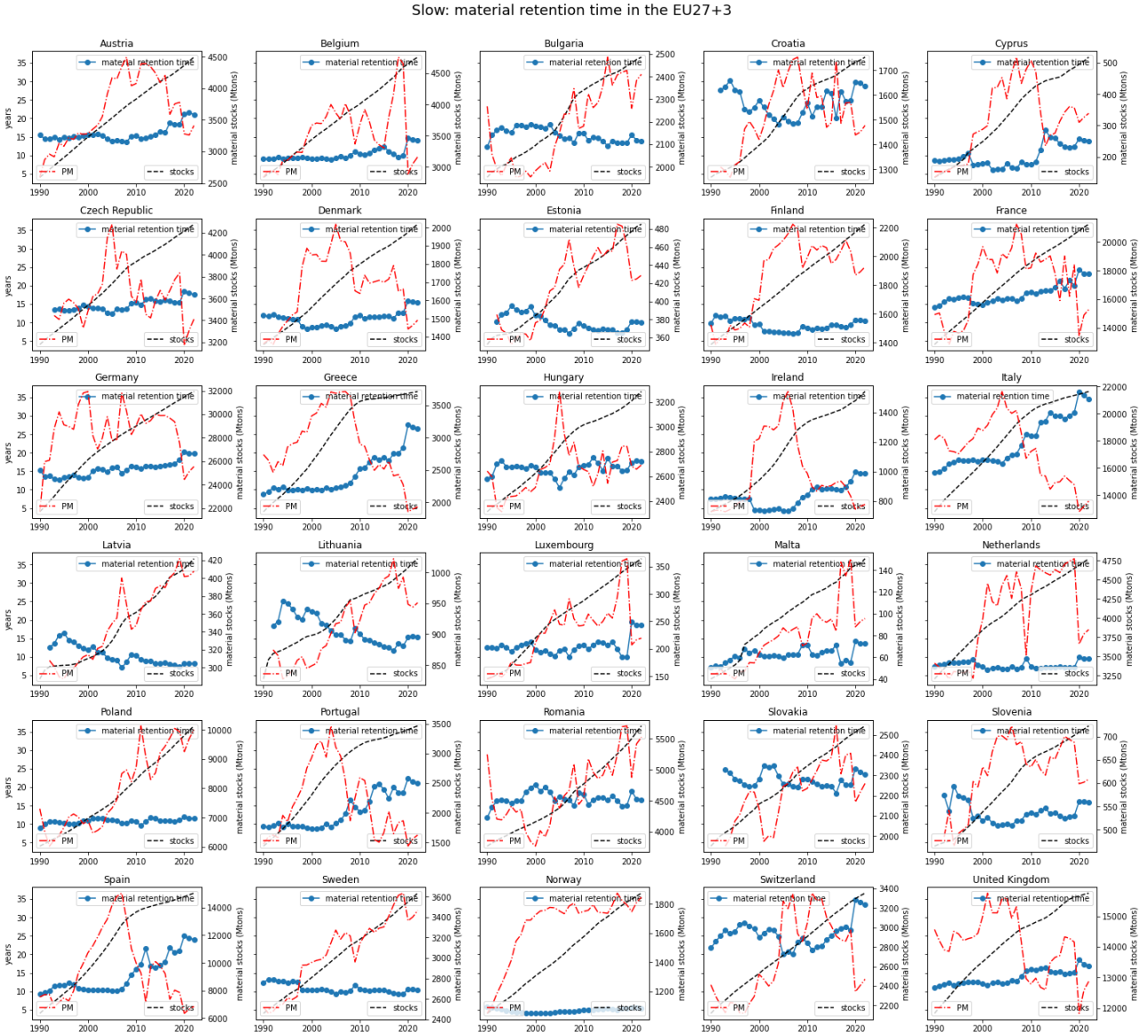


Figure 29: Temporal developments of material retention time (MRT), material stocks, and processed materials (PM) in EU27+3 countries (see methods section 5.4 for indicator details).

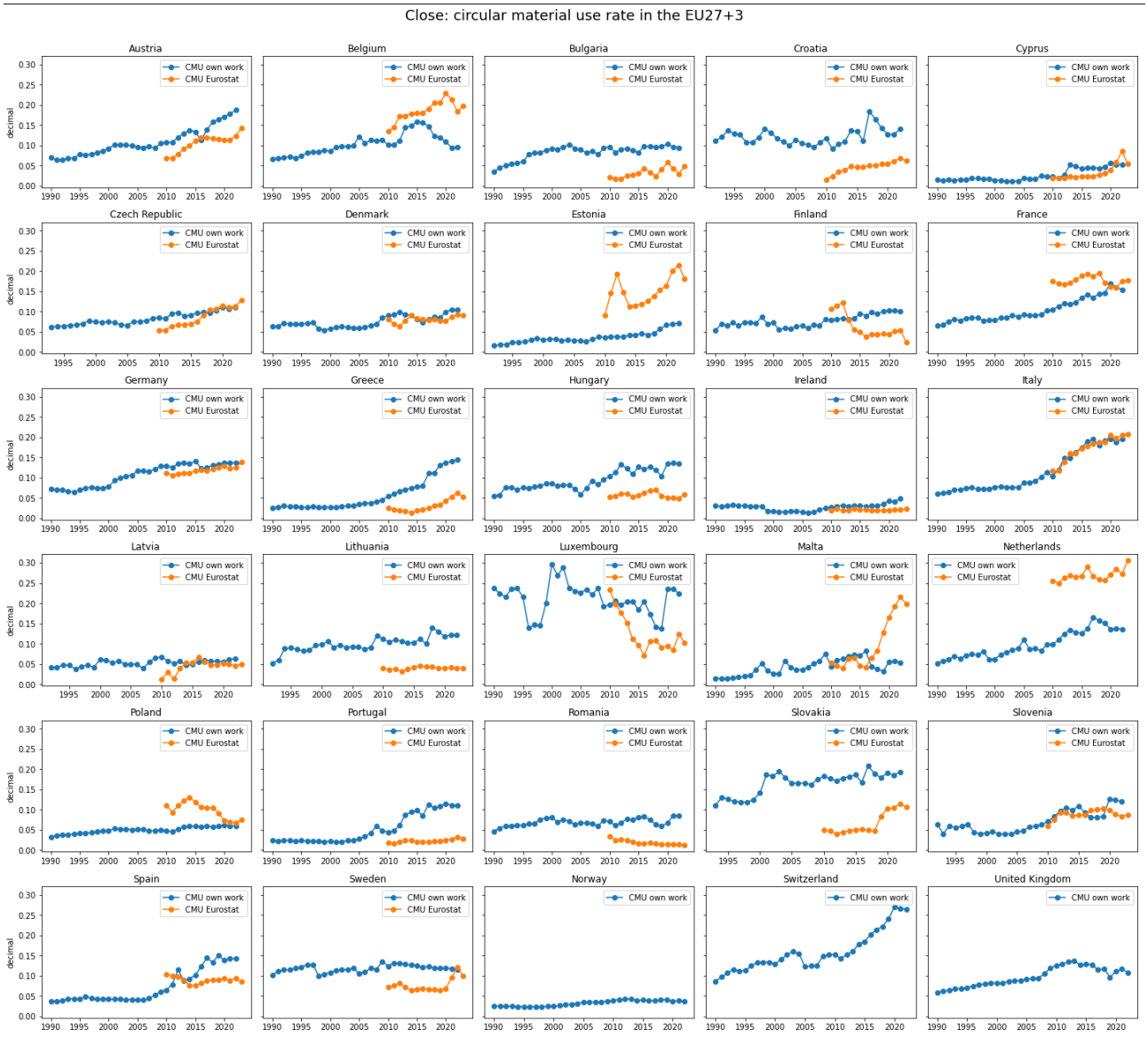


Figure 30: Temporal developments of circular material use rates (CMU) in EU27+3 countries (see methods section 5.4 for indicator details).

9.4. IO-based footprints analysis and the balancing of the extraction-production accounts

Figure 31 shows the results of the diagnostic tests for the RAS balancing run for international trade data and selected metals (iron, steel, aluminium, manganese, zinc, chromium, nickel and lead) in 2022. The figure illustrates how the reconciliation algorithm adjusts the original import and export data to balance the processes and align the physical input-output (IO) tables with the constraints set by the primary production data (MISO) and the raw material extraction data (IRP). Various indicators that compare raw data and the final results are presented.

In absolute terms, iron ore exports from South Africa and Canada as well as iron ore imports to China, are the trade flows most affected by the balancing algorithm (yellow colour in top heatmaps in Figure 31). When viewing the differences between raw and final data in relative terms by material (i.e. the share of each region in the total material difference across all countries), we see that imports to China (iron and steel, manganese, chromium, and tin) and South Korea (zinc) are most affected by the RAS balancing process (bottom heatmaps in Figure 31). Using the hypothetical mean between raw and final data as our basis (middle heatmaps in Figure 31), we can see that several smaller trades (material-region cells in the bottom right corner of the heatmaps) are altered more strongly (yellow colour). Regarding larger trades, we observe that the algorithm significantly modifies imports of manganese to Turkey and exports of manganese from India, as well as imports of aluminium to Malaysia.

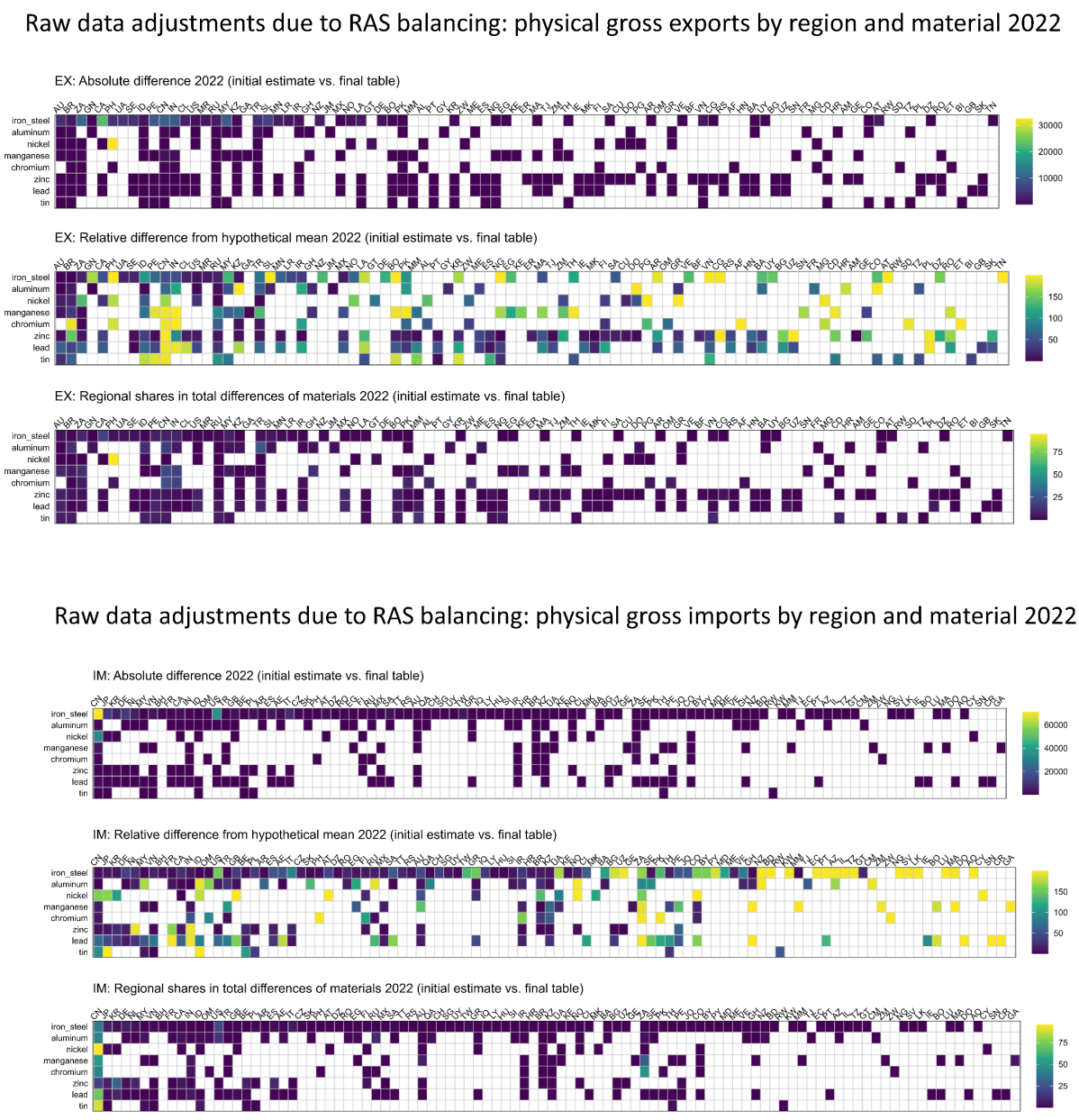


Figure 31: Heatmaps of the changes in the raw data of regional gross imports (top) and exports (bottom) due to the RAS balancing run depicted in terms of three different metric by selected metals and all countries that are reported by BACI trade data. Yellow depicts large and blue small differences. Heatmaps at the top show absolute differences between raw data (initial estimate) and final results in the physical IO table [kt/year]. The middle heatmap shows changes between raw data and final result in terms of the hypothetical mean of raw data and final results [%]. The bottom heatmap shows the share of regions in the total differences for each material [%]. Results refer to the year 2022. Countries and materials are sorted in descending order of the mass of the trade flows showing the largest absolute flows in the top left and the smallest in the bottom right corner of the heatmap.

Figure 30, Figure 31, and Figure 32 show plots for the RAS updating factors of MISO2 production, the market balancing constraint, and the process balancing constraints, respectively. When updating factors converge to 1, constraint violations diminish. For process balances this means that inputs into processes equal the outputs. For the market balances this means that materials produced equal the materials that are used. Updating factors are useful for diagnosing the quality of RAS balancing runs because they are normalized representation of constraint violations. However, a large updating factor (e.g., 100) does not necessarily represent a large absolute violation between true value and realized value (because 0.05/5.00 = 1/100).

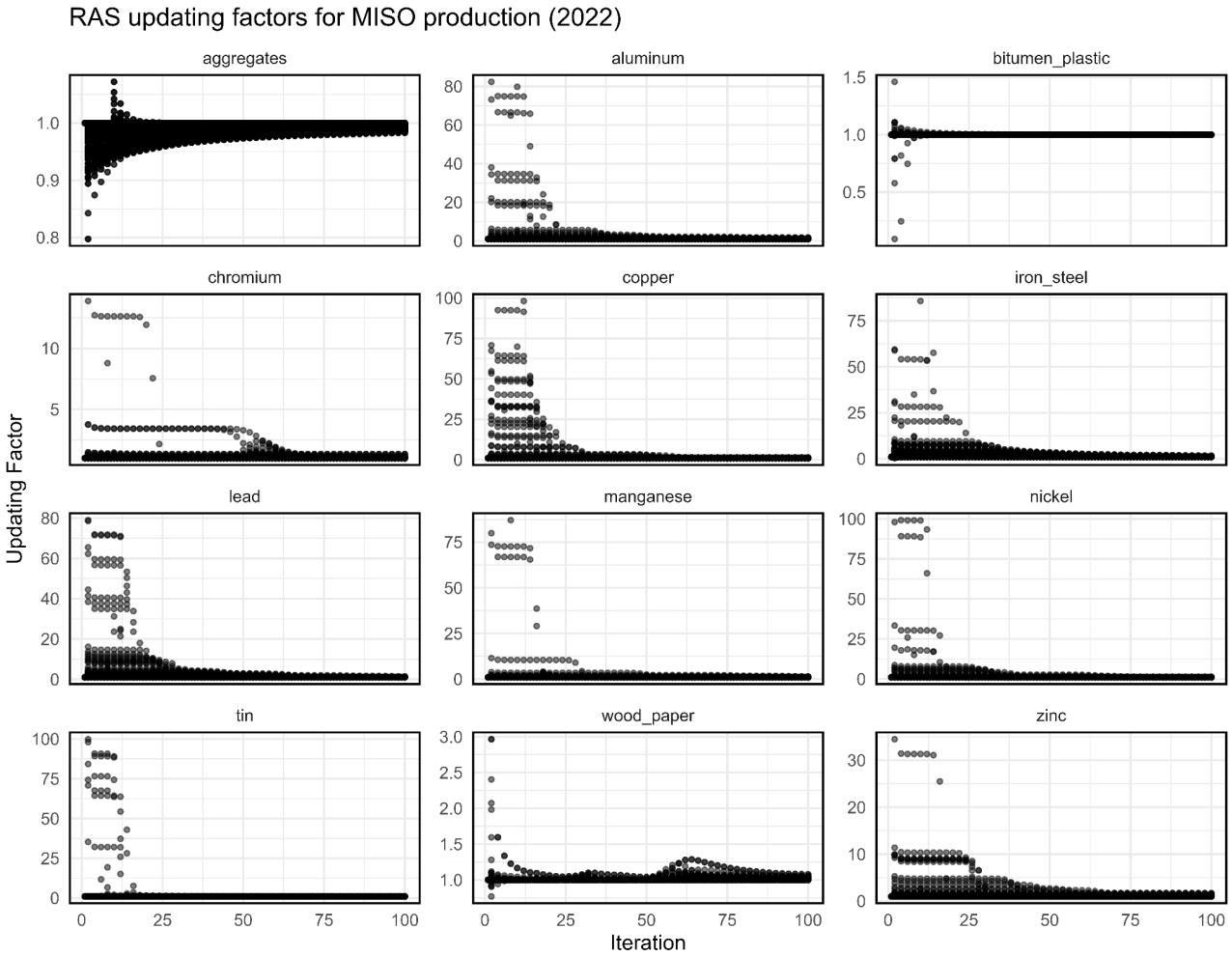


Figure 32: Overview over the RAS updating factors of MISO production data constraints, all materials year 2022. Only the first 100 iterations and updating factors smaller than 100 are depicted for better visualization. Convergence to 1 indicates constraints are realized in the estimated table.

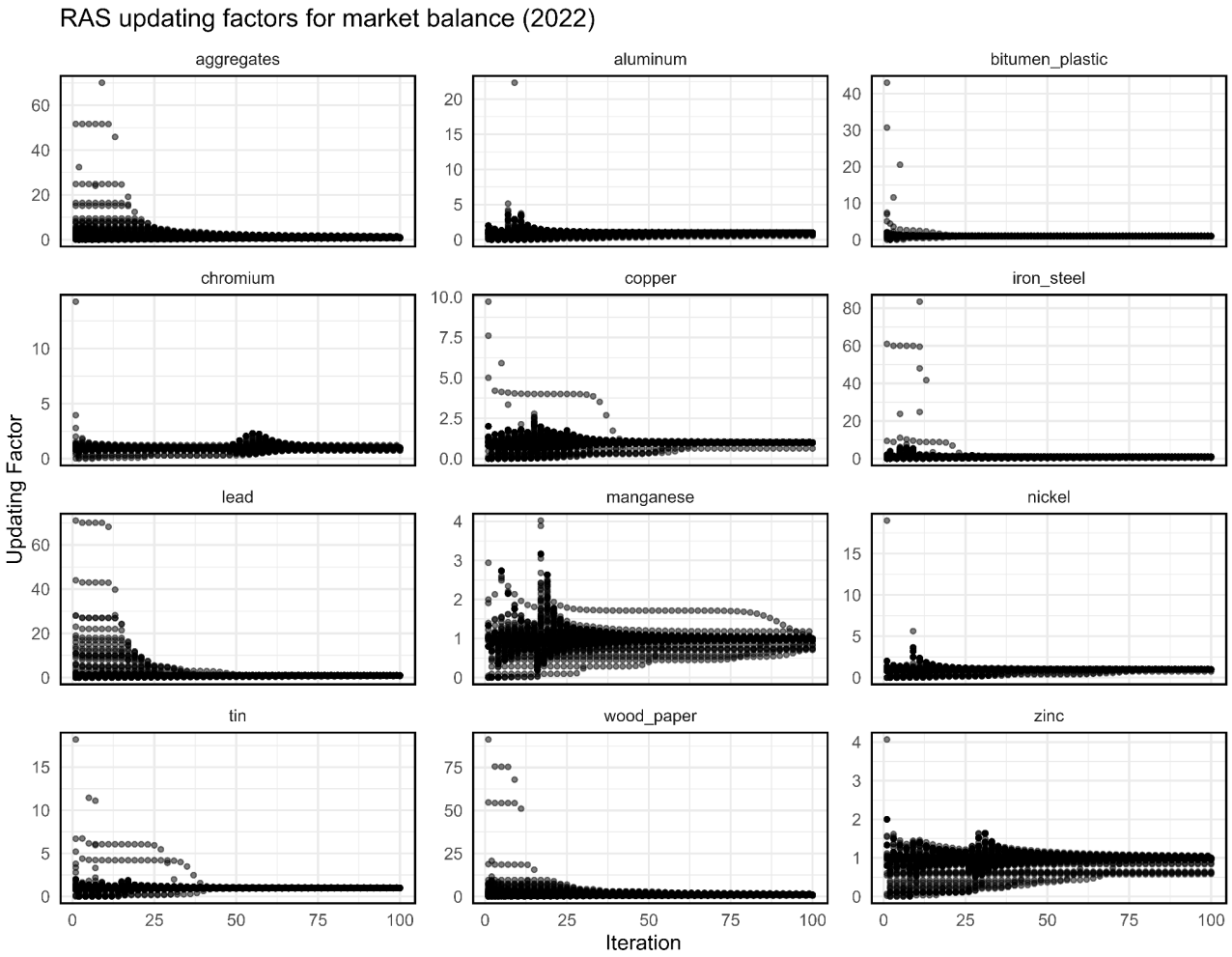


Figure 33: RAS updating factors for market balances. All materials for 2022. Only the first 100 iterations and factors smaller than 100 are depicted. Convergence to 1 indicates constraints realization in the estimates IO table.

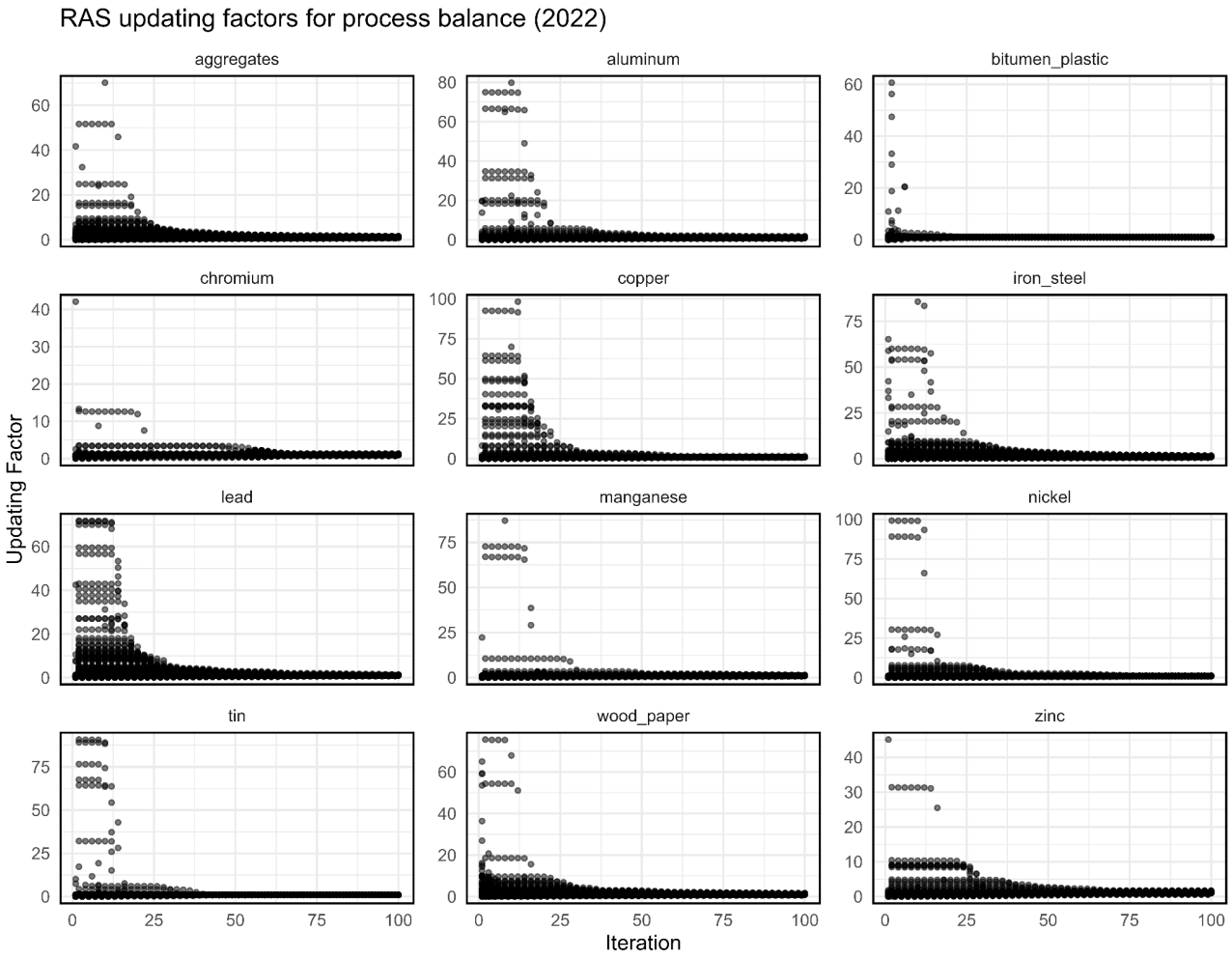


Figure 34: RAS updating factors for process balances. All materials for 2022. Only the first 100 iterations and factors smaller than 100 are depicted. Convergence to 1 indicates constraints realization in the estimates IO table.

Figure 33 provides an overview of the relative distribution of total raw material extraction, related energy use and CO_2 emissions for all stock-building materials. It shows that approximately 30% of global stock-building material extraction is for metals and around 65% for non-metallics. The latter including sand and gravel, as well as limestone, clay and ornamental stone. Metals account for the largest proportion of CO_2 emissions (around 57%) and energy use (52.5%) related to extraction. Although biomass and fossil fuel extraction for stock-building materials are rather small on a global scale (around 2–4% each), they account for significant shares of the energy use and CO_2 emissions related to the extraction of stock-building raw materials (10-17%). This highlights the relatively high energy intensity of these materials compared to others. Non-metallics have the lowest extraction-based energy intensity, which is why their contribution in terms of energy and greenhouse gases (GHGs) is smaller (18-22%) compared to their contribution in terms of extraction volumes (65%).

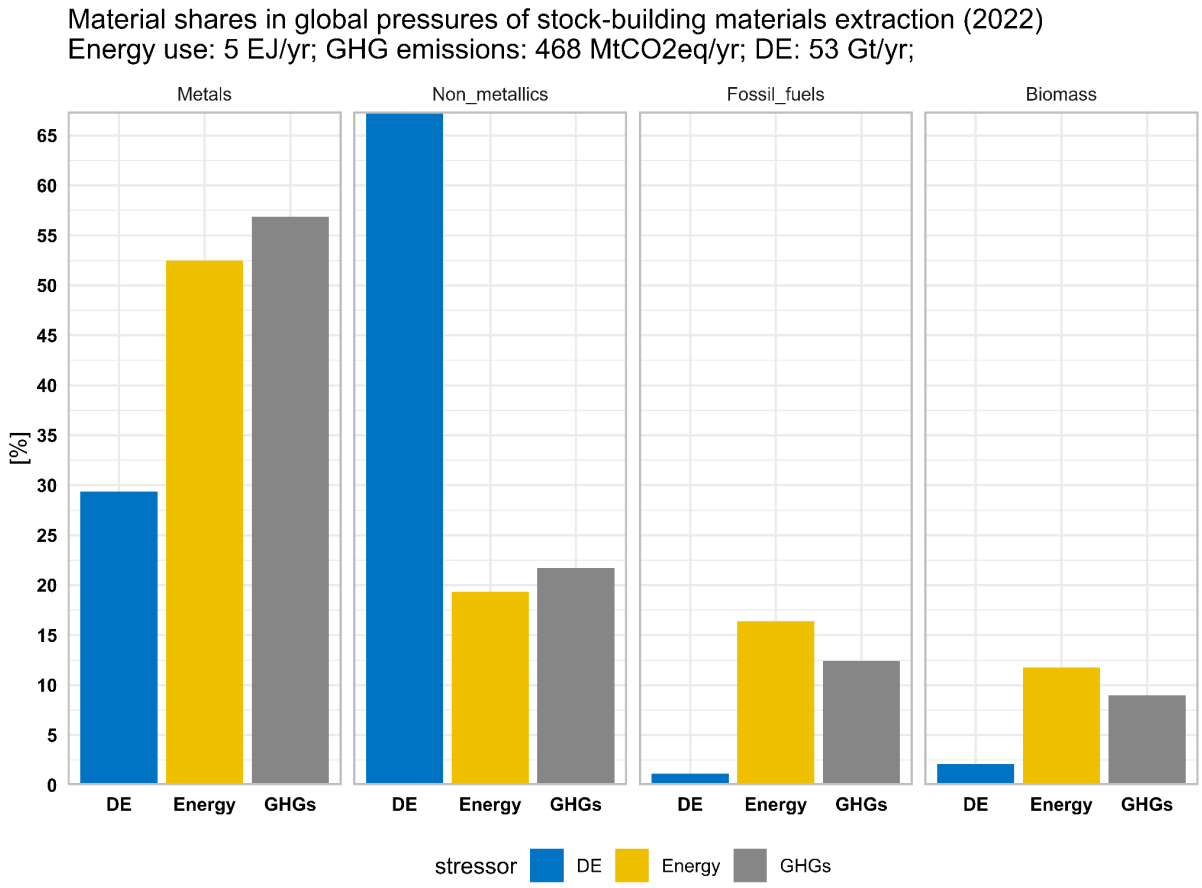


Figure 35: Relative distribution of production-based raw material extraction (DE) and extraction-related final energy use and CO2 emissions across all stock-building material groups for the year 2022. Raw materials that are not modelled in the physical IO tables, such as limestone or clays and silver ores, are also depicted here.

Figure 34 shows additional footprint results for the trade analysis of the EU27+3 that is presented in the result section (year 2022). The figure shows raw material extraction embodied in the imports and exports of the EU27+3 across different stock-building material processing chains divided into source and destination continents of these flows for the year 2022. in absolute terms, are predominantly going to Asia (yellow bars) and Africa (red bars). For wood and paper we see that ca .48 Mt/year of timber exports are going to paper and wood production in Asia. For some metals like chromium and manganese, Africa accounts for a large part of exports. With regard to imports, around 4 Mt/year of bauxite is imported from Africa. The largest import flow with ca. 180 Mt/year is found for iron ores from America (i.e. Brazil).

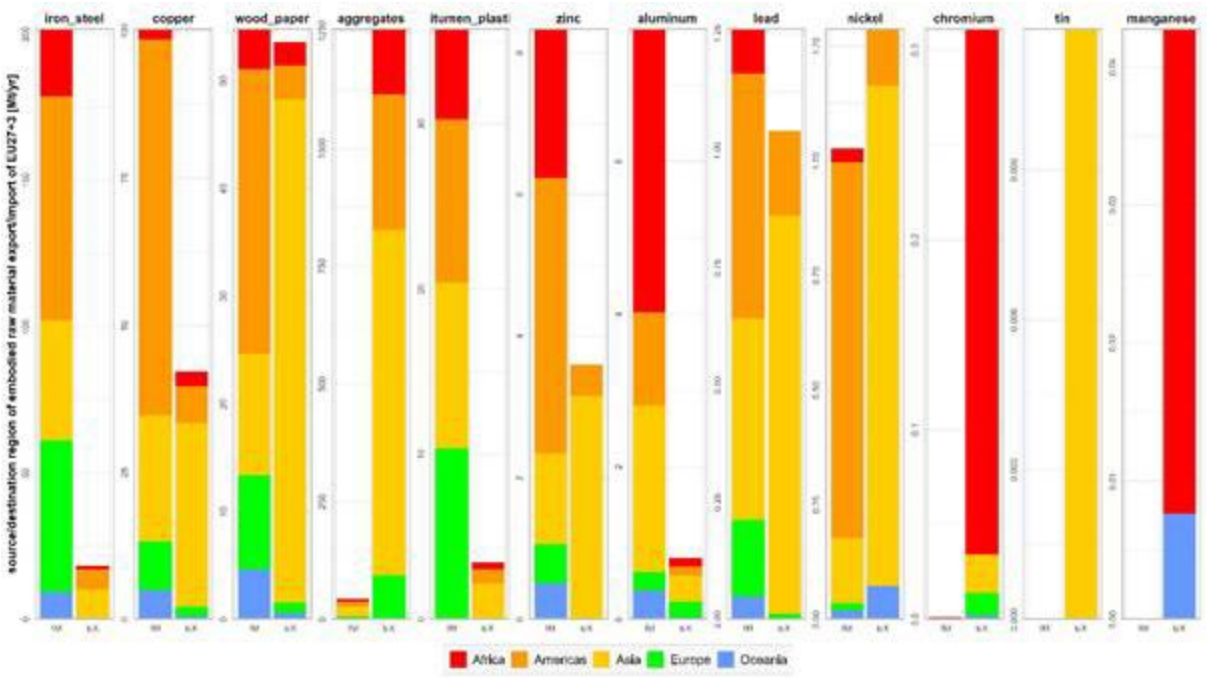


Figure 36: RME in imports/exports of EU27+3 by material (processing chains) and source/destination continent. Year 2022 in units of Mt/yr. The region group "Europe" shown here refers to countries classified as Europe that are not listed in the EU27+3 (e.g., Serbia, Bosnia and Herzegovina or Ukraine). Please note that the materials are sorted from left to right in descending order of RME in imports. Materials have different scales on the y-axis.

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